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MINERALS AND MINERAL DEPOSITS

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Minerals and Mineral Deposits

A CONSPECTUS

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PREFACE

THIS BOOK is not an addition to the ever-growing number of manuals on Mineralogy which deal with the systematic description and methods of identification of minerals. It is an ambitious attempt to interest the general reader in many aspects of the subject of Minerals, including their shape and internal structure, physical characters, mode of occurrence in rocks, and their importance in world affairs before and during the Industrial Age. It aims also at telling something about the geological processes of formation of economic mineral deposits, the search for new occurrences, the operations involved in the winning of industrial minerals and metals, and the distribution of mineral resources throughout the world. If the book encourages the reader to learn more about the many-faceted subject of Minerals it will have achieved a useful purpose.

May, 1948.

W. R. J.
D. W.

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CHAPTER I

INTRODUCTION

FORMERLY IT was customary to classify all natural objects into three great groups or kingdoms—animal, vegetable, and mineral. The first two embraced everything organic, whether living or dead, whereas the mineral kingdom comprised the whole inanimate world including minerals, rocks, soils, and the 'waters of the earth'. Minerals are the materials out of which nearly all the rocks of the earth's crust are built. They are, strictly speaking, inorganic products of nature made up of chemical elements or compounds, though a few substances of organic origin such as coal, pearl, coral, and the fossil resin, amber, are often described as minerals. It is true that the chemist and metallurgist are able to prepare many substances possessing exactly the same composition and physical properties as minerals found in nature, but their laboratory and furnace products are classed apart as artificial minerals.

Although we live in a world mainly composed of minerals few people realize the extent to which the quest for minerals and their utilization have influenced the course of history. From the remote times when our prehistoric ancestors sought flints for making implements until the present day when our contemporaries search for uranium-bearing minerals to manufacture atomic bombs and utilize atomic energy, minerals have played an increasingly significant role in world affairs. Indeed, we have become so dependent upon the products of the mineral kingdom that it taxes the imagination to visualize life without them, for they provide us with the material for most of our buildings and domestic appliances, our lighting and power, our means of transport on land and sea and in the air, the mineral fertilizers vital to agriculture, and a vast array of implements and machines used both in peace and in war. Even before the industrial era the lure of minerals, and especially the craving for precious metals, had profoundly affected the trend of history by encouraging exploration and commerce, inciting conquest, and promoting the spread of civilization.

During the past one hundred years the volume and variety of mineral production have grown so much that the ramifying influence of the mineral industry now pervades the whole fabric of human activity. Within this period the annual output of iron, the master metal of our age, has multiplied a hundred-fold, that of copper more than sixty-fold, and the production of many other metals and minerals has increased to an even greater degree. So rapidly has the exploitation of minerals accelerated that more of them have been extracted from the earth during the past forty years than in all preceding history.

The rising trend of mineral production has kept pace with the expanding volume of industrial output. When industry thrives the yield of minerals increases, and in times of industrial depression their production correspondingly declines. The curves shown in Fig. 1 illustrate the growth in the annual production of several essential metals between the years 1880 and 1944, and depict how the general rise in metal output was interrupted sharply by the post-war slump of 1921 and again by the world depression of the early 1930's. Thereafter, production increased owing largely to active

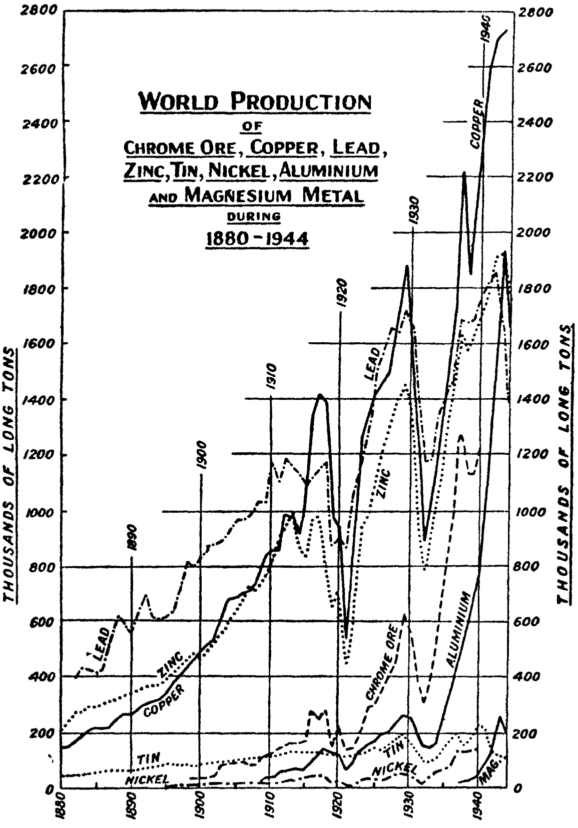


Fig. 1. World Production of some Essential Metals, 1880–1944.

preparations for war in many countries and the amassing of mineral stocks necessary for the manufacture of armaments. During the sixty-four-year period mentioned there were analogous trends in the production curves of nearly all mineral products, including iron, manganese, mica, asbestos, coal, and petroleum. The output of pig iron multiplied more than five-fold, reaching over a hundred million tons in 1940, and there was a proportional increase in the extraction of manganese ore indispensable for the making of steel.

Coupled with the vast expansion in mineral output there has also been, particularly during the past twenty years, a growing demand for more varied supplies until now more than a hundred different minerals are employed in industry. Many elements formerly considered as 'rare', such as beryllium, cadmium, cerium, lithium, radium, selenium, tantalum, uranium, and zirconium are now in everyday use, and several minerals that were commercially useless two decades ago have since then entered the widening field of industry. Within recent years, too, there has been a phenomenal increase in the production of minerals used in the manufacture of aluminium and magnesium for light alloys embodied in the construction of aircraft, automobiles, railway carriages, and so forth.

In the rapidly expanding chemical industry no single commodity plays a more important role than sulphuric acid, which is obtained almost entirely from two minerals, iron pyrites and sulphur. Indeed it has been asserted that a nation's consumption of sulphur is a measure of its industrial progress, for few manufacturing processes fail to utilize it in some form or other. It is not surprising, therefore, that the exploitation of sulphur-bearing deposits has proceeded apace during the present century. The ever-growing need for food has entailed an increasing demand in agriculture for mineral fertilizers which provide plants with essential phosphorus, potassium, sulphur, and nitrogen. Within the past thirty years the annual production of these fertilizers has been more than doubled.

The present century has witnessed such an enormous increase in the use of Portland cement in the construction of roads and buildings that we might justifiably refer to modern times as the 'cement age'. World production of this cement, which is manufactured essentially from limestone and clay, now approaches a hundred million tons a year and thus ranks as one of the most important branches of the mineral industry. The vast expansion in building has also resulted in a spectacular growth in the consumption of gypsum for the manufacture of plasters, laths, and wallboards, the annual world output of gypsum being now about ten million tons. Finally, we may note that among the many other non-metallic minerals whose production has soared during the past forty years are asbestos for use in fireproof materials, clutch facings, and brake linings; ilmenite for titanium paints; borates for enamels, glazes, and glassware; and industrial diamonds for dies, drills, and machine tools.

In answer to the question, *what is a mineral*, we can certainly say that no definition will satisfy everybody, for the geologist, the miner, the lawyer, and others use the term with different meanings. To the geologist the great majority of minerals are inorganic substances, each possessing a characteristic chemical composition and usually a definite crystalline structure which, under favourable conditions of growth, is expressed by a regular external shape or form. As regards the chemical composition a certain latitude is permissible providing it does not entail any radical distortion in the atomic structure of the mineral. For example, when pure the common ore-mineral zinc blende is composed solely of zinc and sulphur atoms, but a considerable proportion of the zinc may be replaced by iron without the mineral losing its original identity. Similarly the well-known mineral orthoclase, or potash felspar, contains variable amounts of soda, though when all the potash is replaced by soda the felspar undergoes a change in crystalline character and is then called albite or soda felspar.

On the other hand, the same chemical substance sometimes exists in the form of two or more quite distinct minerals. For instance, carbon occurs in nature as diamond, the hardest of minerals, and also as graphite, one of the softest; similarly, the compound calcium carbonate may crystallize in two markedly different modifications as the minerals calcite and aragonite, whose internal structures are fundamentally unlike.

Although an almost endless number of compounds can be formed from the various chemical elements yet the number of mineral species is restricted. It is true that more than 1,500 minerals have been described and recognized by mineralogists as genuine species, but a list of 200 would embrace all the common ones, including those of economic importance. Actually the bulk of the earth's crust is composed of but six mineral groups, namely felspar, quartz, mica, pyroxene, amphibole, and olivine.

Natural ice is a mineral, for it has a definite composition, H_2O, and its internal structure is as truly crystalline as that of the most perfect snow-crystal with its exquisite hexagonal symmetry. In the popular conception all minerals are solids, but water and mercury, which are both liquids at ordinary temperatures, are accepted by the mineralogist as specific minerals.

To the layman and the lawyer almost anything of economic value that can be won from the earth, such as coal, oil, limestone, or slate, is regarded as a mineral. In the strict sense substances of this kind are not minerals, though they do belong to the mineral kingdom and are included in statistical lists of mineral production issued periodically by the governments of various countries. To the geologist, however, coal, granite, clay, sandstone, and marble are all classed as rocks because they are mixtures or aggregates of different minerals.

If we examine closely the well-known rock called granite, so commonly used as an ornamental stone, we can see with the naked eye that it is made up of at least three components. In fact, the granite is very largely composed of three essential constituents, quartz being the colourless glassy material with irregular outline, felspar the milky-white or flesh-coloured substance with rather smooth surfaces, and mica the soft glistening black or silvery-white material which can be readily split into thin scales. These rock constituents are called minerals, each having a characteristic chemical composition and consistent physical characters. Some rocks consist wholly or almost wholly of one component; for example, pure marble is made up entirely of the mineral calcite in the form of an aggregate of interlocking units, and sandstone is mainly composed of somewhat rounded transparent grains of quartz.

In general, *minerals form either from solution, from fusion, or by sublimation from vapours.* Crystallization from solution is exemplified by the growth of salt crystals, cubic in form, which separate out during the slow evaporation of an aqueous solution of sodium chloride. Other crystals may be produced by lowering the temperature of a saturated saline solution, or by reducing the pressure sufficiently to induce supersaturation and the precipitation of crystalline salt. Minerals form from a fused molten lava in much the same way as ice crystals develop when water freezes, for water can truly be regarded as fused ice. As the lava, or molten rock material, cools the elements group themselves into various 'molecules' which cluster together to build the individual mineral grains of the resulting solid rock, the growth of large crystals being promoted by very slow cooling. A few minerals result from the interaction of gases, or by crystallizing from vapour just as snow crystals form by condensation of water vapour in the cold upper layers of the atmosphere. Bright yellow crystals of pure sulphur commonly grow in this way near the crater rims of active volcanoes, as a direct sublimation or cooling product of sulphur-bearing vapours.

CHAPTER II

MINERALS IN WORLD HISTORY BEFORE THE INDUSTRIAL AGE

LONG BEFORE civilized man learned to use metals the influence of minerals had deeply affected the lives of his Stone Age ancestors. Earliest man is known to us by the flints he fashioned for implements, some of which may have been shaped by him 500,000 years ago, before Britain was invaded by the great ice-sheets of the Pleistocene period. Palaeolithic flint scrapers and hand-axes made by successive races of early man have been discovered in caves and old river terraces, the pressure-flaked implements fabricated by Solutrean man more than 20,000 years ago being of exquisite workmanship. The earliest flint tools were made from material collected from the surface of the Chalk or from river pebble-deposits, but during Neolithic times systematic mining for flint in the Chalk beds of England and France was actively pursued. This actually represents the oldest known form of underground mining.

Palaeolithic man was an inveterate user of paints, his marvellous paintings on the walls and roofs of grottoes being coloured with mineral pigments, such as red and yellow ochres consisting of iron and manganese oxides mixed with clay. At a very early period he carved soft stones into ornaments and utensils. The working of clay for pottery, begun in Palaeolithic times, became widespread during the Neolithic age and was undoubtedly the first large-scale mineral industry. Between 100,000 and 7000 B.C. primitive man is said to have used about fourteen different varieties of semi-precious and decorative stones, including chalcedony, rock crystal, serpentine, obsidian, pyrite, amber, jadeite, calcite, amethyst, and fluorspar. Gems and precious stones, 'the flowers of the mineral kingdom', have been prized for their beauty since prehistoric times and were diligently sought by the early Egyptians, Babylonians, Assyrians, and Indians. More than 5,000 years ago the Pharaohs dispatched expeditions to the Sinai Peninsula in quest of turquoise, probably the first gem-stone to be mined extensively, and the ancient Egyptians sank hundreds of shafts in search of emeralds on the coast of the Red Sea. It was the fascinating colour of the stones, such as the blue of turquoise and lapis lazuli, the purple of amethyst, the red of garnet, and the green of malachite, that prompted early trade in these minerals. Apparently the diamond was not an article of commerce until about 700 B.C. and did not attain industrial importance before A.D. 600.

Salt played a significant part in influencing the course of trade in the ancient world and has long been the cause of strife between peoples. The salt oasis of Palmyra was the meeting point of the great trade routes from the Phoenician ports to the Persian Gulf and from southern Arabia. Caravan tracks through the Libyan Desert converged on the salt springs, and at the time of Alexander the salt mines of India were a focus of trade. It is probable that salt, obtained from works established on the banks of the Tiber about 625 B.C., was the first mineral to provide a source of revenue to the Roman state. Incidentally, the word 'salary' originally referred to the money paid to a Roman soldier to buy his much-needed salt. In Germany the great salt deposits were being worked vigorously during Celtic times in mines reputed to be the oldest in Central Europe. These *saltz stocks* were the cause of bitter wars between the German tribes during the reign of the Caesars. In countries where salt is scarce the mineral has served since time immemorial as a basis of taxation under government monopoly.

Metals were first used by primitive man as ornaments. The earliest to attract attention was gold, which Neolithic man discovered as glistening nuggets in the sands and gravels of many streams. The bright metal proved so malleable and so resistant to tarnish that it became, and still remains, the ornament *par excellence.* Copper, which may occur naturally in 'pure' metallic form at or near the surface, was also used for decorative beads and bangles during the Stone Age. Since copper is a soft metal that can be hardened easily by hammering, primitive man soon learned to fashion it for more practical purposes into knives, arrowheads, and spear points. The metal is said to have been known to the Egyptians before 12000 B.C., and the art of hardening copper by hammering was certainly known to the Chaldeans nearly 6,500 years ago. Silver, another soft element found in nature, was also of early use, the art of shaping silver vases and jugs being well advanced by 2500 B.C.

The fortuitous discovery in the camp-fire that metal could be melted out of the rock was an event of immense portent, for it heralded the Age of Metals in which we now live. This crucial event seems to have happened little more than 5,000 years ago, when the first primitive smelting of copper yielded a spongy mass of metal capable of being beaten into tools. Not long afterwards the practice of casting began and copper implements were then shaped by pouring the molten metal into stone moulds. Silver and lead, being easily reduced from their shining ores, were among the earliest products of the rudimentary furnaces. In the ruins of Hissarlik (later named Troy) were found shapeless lumps of lead believed to date back to nearly 3000 B.C. and the metal is thought to have been used by the Chinese for debasing coinage before 2000 B.C. Lead was later employed by the ancients for ornaments, sling-shot and, especially in the days of the Roman Empire, for water-pipes, remnants of which were found in the buried cities of Pompeii and Herculaneum.

In many regions, such as Cornwall, Bohemia, and China, copper and tin ores occur in close association and it is not surprising therefore that bronze, the alloy of these two metals, was produced at an early date. The use of bronze, which is considerably harder than copper and thus more useful for manufacturing implements, began in Europe before 2000 B.C., possibly more than 500 years before tin (which does not occur naturally as a metal) was smelted from its oxide, cassiterite. Similarly, the intimate association of copper and zinc in certain districts led to the production of brass for making ornaments and utensils, though the metal zinc was not discovered until 1509, at the close of the medieval period. Bracelets made of brass were unearthed from the ruins of Kameiros, on the island of Rhodes, burnt in the sixth century B.C.

Iron is a very common constituent of the earth's crust, yet the purposeful production of the metal by smelting did not take place for thousands of years after copper, silver, and lead had first been reduced from their ores. Although iron appears to have been known to the Egyptians as early as 3500 B.C. the surviving iron relics belonging to these remote times were almost certainly made from malleable meteoric iron. For long the metal was so rare as to be more highly prized than gold. Iron knives dating back to 1350 B.C. were discovered near Gaza in Palestine, but not until about 1200 B.C. was man able to fabricate useful tools such as hoes, sickles, and ploughshares from the iron extracted from ore. Even then the primitive founder could only produce a spongy mass of metal capable of being hammered in the forge, and the actual smelting of iron ore to yield 'cast' iron, which requires a temperature of 1,500° C., was not accomplished until about the fourteenth century. The use of iron for weapons and implements was widespread throughout Europe by the time Caesar landed in Britain. From then onwards, as we shall see later, its influence on human history expanded continuously until it became the very backbone of modern civilization.

The panorama of human activity during the past 3,000 years has been profoundly affected by the lure and possession of minerals, and the march of civilization has kept pace with development in the art of utilizing minerals. In the long history of Egypt before the Christian era much of her wealth, trade, and military record was bound up with the quest and acquisition of metals, particularly from the gold mines of Nubia and the copper deposits of Sinai and Cyprus. In exchange for her metals and turquoise there came silks, spices, and gems from the Orient, and trade flourished with the gold-loving kings of Assyria. Copper and later iron furnished weapons for the conquering soldiers, and with the amassing of metals Egypt attained the zenith of her power about 1400 B.C., during the reign of Amenhotep III.

It was the search for metals that led the seafaring

Cretans and later the Phoenicians to dominate trade throughout the Mediterranean for about 2,000 years before the birth of Christ, and to undertake perilous voyages of exploration. They discovered gold, silver, copper, and tin minerals in the hills of Spain and in other lands bordering the inland sea and carried copper from Cyprus and Greece. The intrepid Phoenician metal-merchants reached Cornwall, the famed Cassiterides, about 600 B.C., from whence they shipped tin to the eastern Mediterranean lands, for making bronze weapons. It was the rich mineral wealth of Spain that contributed most to the power of Tyre and led to colonization of the west. The Carthaginians, who followed their Phoenician ancestors into Spain, owed their ascendency largely to the silver obtained from the mines of Andalusia, with which Hannibal and other generals hired mercenary troops to fight their Punic Wars with Rome. Possession of the Spanish mines was indeed a prime cause of the long struggle between Carthage and Rome, for the Romans needed silver for their currency and for trade with the East. It is significant that the power of Carthage declined rapidly after she was driven from Spain and deprived of precious metals.

Much of the history of Ancient Greece is intimately linked with that of the famous silver mines of Laurium, near Athens. Her prosperity during the Golden Age was in large part due to the successful exploitation of these mines, for 'Laurium was a fountain running silver, a treasure of the land' during the heroic days of Greece. It was the silver of Laurium that enabled Themistocles to build ships of war, with which he defeated the Persians at Salamis in 480 B.C. and thereby turned the tide of human history by saving Europe from Persian domination.

About 150 years later the gold of Mount Pangaeus in Macedonia provided treasure which enabled Alexander the Great to equip and finance his first campaigns.

The Romans in their turn owed much to mineral wealth derived by conquest and plunder. An empire gained by the sword was largely maintained by the flow of metals from tributary lands. By vanquishing Carthage the silver, gold, copper, iron, and mercury of Spain became the spoil of Rome; by conquering Britain she acquired copper and lead; and by subjugating Greece and Asia Minor she gained control of their metallic riches. Eventually, with the gradual exhaustion of mineral resources abroad, the supply of metal for trade with the East dwindled and thereby contributed to the decline and fall of the Roman Empire. Thereafter, the Dark Ages settled on Europe and mining remained virtually at a standstill for 400 years, until Charlemagne and his successors began to exploit the gold, silver, and lead deposits of Central Europe. In the tenth century the discovery of silver veins near Goslar initiated a mining industry in the Harz mountains of Germany which helped to finance Otto the Great in his campaigns of empire. From this cradle of the real art of mining the Saxon miners led a migration of the German population eastwards towards the rich lead-silver deposits of Freiberg, discovered in 1170, and subsequently to the precious metal mines of Silesia. The expanding output of silver in Germany throughout medieval times assured her the commercial supremacy of Europe, and during this period mining progressed from predatory exploitation to the status of a basic and beneficent industry.

It was the quest for precious metals that led to the discovery and exploration of the New World. Columbus, sailing westwards in search of a new route to the Indies and the land of the Great Khan, was lured on by the prize of gold, pearls, and other riches. From the Bahamas, where he first landed in 1492, he journeyed southwards to Cuba and then to the island of Haiti in the hope of finding the phantom El Dorado. Some twenty years later a small band of Spanish adventurers, led by Cortés, reached Mexico, where their lust for conquest was roused by Montezuma's display of gold and silver ornaments. The subjugation of Mexico was quickly followed by other piratical expeditions by the gold-loving Spanish *conquistadores*, culminating in Pizarro's conquest of Peru. After robbing the natives of ornaments and plundering their graves the Spaniards exploited the precious metal deposits, including the fabulously rich silver veins of Potosí, and throughout the sixteenth century treasure poured from many parts of South America into the coffers of Europe. Upon these riches was founded the short-lived hegemony of Spain, which ended with the seizure of Spanish galleons by Drake, Hawkins, and other English privateers. The booty thus diverted not only impoverished Spain but also helped Queen Elizabeth to build the navy which defeated the Armada in 1588. At about this time the influx of precious metals into Europe was so great that the price of commodities rose and brought in its train increased industrial and agricultural activity and a wider pursuit of learning.

By the end of the seventeenth century the continued use of charcoal for smelting iron had resulted in such destruction of the English forests that growing attention was directed to coal as a metallurgical fuel. In 1709 Abraham Darby started to smelt iron at Colebrookdale in Shropshire, using coke in the blast-furnace, and from then onwards there was a rapid increase in the utilization of coke for smelting. This, coupled with the invention of the steam-engine in 1768, heralded England's world supremacy in the production of steel and her industrial predominance during most of the nineteenth century. Apart from the national characteristics of her people England was fortunate in possessing large deposits of coal and iron in close proximity, and to this happy circumstance we must ultimately ascribe her pre-eminence in world affairs during Victorian times. The rise of other industrial nations, notably France, Germany, the United States, and latterly the Soviet Union, was also due mainly to the fortuitous occurrence of extensive deposits of coal and iron closely grouped within their own borders.

Within the past hundred years mineral discoveries in many parts of the world have profoundly affected the course of history. Two events of momentous significance happened during the opening years of the industrial age in England. The accidental discovery of gold in the tail-race of a sawmill in California in 1848 led to the great gold rush of '49. Within a decade the population of California was more than quadrupled, the diggings had yielded about £100 million in gold, and the little-known country between the Mississippi and the Pacific had become the scene of intensive exploration and settlement. The gold of California was an invaluable financial asset to the North in its struggle against the South during the Civil War, and consequently played an important role in maintaining the political unity of the United States. In 1851 the discovery of gold in New South Wales and at Ballarat and Bendigo in Victoria led to a spectacular rush to Australia, involving the rapid influx of more than a million emigrants from Great Britain.

The remote convict settlement of Australia became a hive of activity and, with the subsequent finding of other mineral deposits, such as the silver-lead ores of Broken Hill, N.S.W., and the gold veins of Calgoorlie, W.A., more immigrants entered the continent to mine, to till the soil, and to build a brave new world.

We may conclude this chapter by recalling that it was the lucky finding in 1867 of diamonds in the Kimberley district of South Africa that led to the industrial awakening of the Dark Continent. The feverish mining of diamonds was followed by the discovery of the world's richest goldfield on the Witwatersrand of the Transvaal and the consequent further quickening of mining activity. Aided by profits from the gold and diamond mines, Cecil Rhodes despatched expeditions northwards to the Zambezi in search of gold, and under his guidance British rule was extended deep into the heart of Africa. It was, as usual, the pioneer miner who went forth to blaze the trail of civilization.

CHAPTER III

THE COMPOSITION OF THE EARTH'S CRUST

To A DEPTH of many miles below the surface the outer solid shell or crust of the earth is composed of a great variety of rocks, the vast majority of which are mineral aggregates. These rocks include soft and loosely compacted materials such as clay, sand, and gravel, as well as hard stony ones like granite, sandstone, and limestone. They may be classified according to their origin into three major groups—igneous, sedimentary, and metamorphic. The *igneous* rocks are those which have solidified from a hot molten rock material called magma. Granite and basalt are two of the commonest types. The *sedimentary* rocks are formed from the soluble and insoluble breakdown products of pre-existing rocks and have been deposited on land or in water, for the most part as layers or strata consisting of disintegrated rock-fragments, organic remains, or chemical precipitates. Sandstones and limestones are typical examples. *Metamorphic* rocks are developed from either igneous or sedimentary types by the action of heat, pressure, and circulating waters, and include marble, slate, and schist.

Although the sedimentary rocks act as a thin blanket covering much of the land surface of the globe, they constitute only about 5 per cent of the total bulk of the earth's crust down to a depth of 10 miles. In studying the composition of the crust as a whole therefore, such familiar sediments as limestone, sandstone, and coal are of much lesser account than the igneous and associated metamorphic rocks which underlie the cover of sedimentary rock and are also exposed over wide tracts. So preponderant are the igneous rocks that we can safely assume their average composition to approximate to that of the outer 10 miles of the earth's crust. From a computation based on about 5,000 analyses, Clarke and Washington estimated the average chemical composition of all igneous rocks to be as shown in the following table.

AVERAGE COMPOSITION OF THE EARTH'S CRUST

In Terms of Elements			*In Terms of Oxides*		
Element	*Symbol*	*Per cent*	*Name*	*Formula*	*Per cent*
Oxygen	O	46·71	Silica	SiO_2	59·07
Silicon	Si	27·69	Alumina	Al_2O_3	15·22
Aluminium	Al	8·07	Iron oxide	Fe_2O_3	3·10
Iron	Fe	5·05		FeO	3·71
Calcium	Ca	3·65	Lime	CaO	5·10
Sodium	Na	2·75	Soda	Na_2O	3·71
Potassium	K	2·58	Potash	K_2O	3·11
Magnesium	Mg	2·08	Magnesia	MgO	3·45
Titanium	Ti	0·62	Titania	TiO_2	1·03
Hydrogen	H	0·14	Water	H_2O	1·30
Phosphorus	P	0·12	Phosphoric oxide	P_2O_5	0·30
		99·46			99·10

As indicated, only eight elements are present in amounts exceeding 1 per cent and these together account for 98 per cent of the earth's crust. Following the elements listed above are carbon (C) 0·09 per cent, manganese (Mn) 0·09 per cent, sulphur (S) 0·05 per cent, chlorine (Cl) 0·05 per cent, barium (Ba) 0·04 per cent, fluorine (F) 0·03 per cent, and strontium (Sr) 0·02 per cent. The remaining elements, including valuable metals such as chromium, copper, nickel, tungsten, zinc, tin, lead, antimony, mercury, silver, gold, and platinum (named in order of decreasing abundance), together constitute less than 0·20 per cent of the crust. It is thus clear that before these metals can be profitably extracted from the ground they must have been highly concentrated by geological processes. In view of the increasing importance of the 'rarer' elements it is significant that, according to the eminent geochemist, V. M. Goldschmidt, rubidium is three times as plentiful as copper, cerium is more common than zinc, yttrium occurs in double the quantity of lead, and the 'atomic bomb element' uranium is 800 times more abundant than gold or platinum.

With a few possible exceptions all the known elements are found in minerals. About twenty elements, including gold, silver, copper, and carbon (in diamond and graphite), may exist in the free or uncombined form and are said to occur in the *native* state. These, however, are rare in comparison with the *silicate* minerals, which comprise more than 95 per cent of the whole earth's crust and are unquestionably the predominant rock-forming minerals. They consist of oxygen and silicon usually in combination with one or more metallic elements such as aluminium, sodium, potassium, calcium, magnesium, and iron, often forming complex chemical structures. Two well-known minerals, quartz (SiO_2) and felspar (e.g. $KAlSi_3O_8$), are the commonest of all the silicates. Among the other chemical classes of minerals we need at this stage only mention briefly the *sulphides*, formed by the union of various metals with sulphur (e.g. galena = lead sulphide PbS); the *oxides*, containing a metal in combination with oxygen (e.g. hematite = iron oxide Fe_2O_3, and cassiterite = tin oxide SnO_2); the *carbonates*, consisting of carbon and three atoms of oxygen, together with a metal (e.g. calcite = calcium carbonate $CaCO_3$); the *sulphates*, compounds of sulphur and oxygen with one or more metals (e.g. barytes = barium sulphate $BaSO_4$); and the *halides*, which include simple compounds of chlorine or fluorine with a metal (e.g. halite or common salt = sodium chloride NaCl, and fluorspar = calcium fluoride CaF_2).

CHAPTER IV

THE SHAPES OF MINERALS

NATURE'S LOVE of order finds one of its most fascinating expressions in the form of minerals that have developed freely and slowly without interruption. Under such favourable conditions of growth nearly all minerals assume definite and characteristic shapes known as *crystals*, which are bounded by plane surfaces (faces) and have the appearance of artificially made solids or cut gem-stones. The word crystal popularly conjures up the impression of clear 'crystal' glass with smooth sparkling facets. But a piece of glass, no matter how perfectly fashioned in outward form, is not a crystal in the scientific sense. Crystallinity is in fact determined, not by external shape, but by the orderly arrangement of atoms within a substance. In glass the atoms are jumbled together and their disposition is devoid of symmetry, whereas in crystals they are arranged in a precise and regular manner. The contrast between the two structures may be likened to that between the chaos of a mob and the disciplined array of a regiment on parade. With few exceptions, such as opal, all minerals are crystalline and even though their outward shapes may be quite irregular they are each characterized by a regular atomic pattern. In favourable circumstances this unique pattern of individual minerals is visibly expressed in the regular beauty of a crystal.

The word 'crystal' is derived from *krystallos*, meaning clear ice, a name which was also applied by the ancient

Greeks to the pellucid colourless variety of quartz (rock crystal) found among the snow-clad peaks of the Alps, in the belief that it was ice made permanently solid by intense cold. Not until the close of the Middle Ages was the term extended to other regularly bounded forms found in nature or obtained by the evaporation of salt solutions. The comparative ease with which rock crystals can be collected made them early objects of study. Indeed, the first triumph of experimental crystallography was won by Nicolaus Steno in 1669, when he carried out measurements on the angles between corresponding faces of many different specimens of quartz crystals.

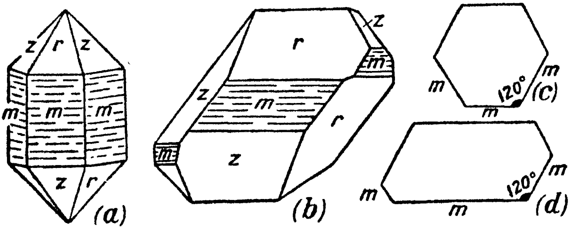


Fig. 2. Quartz. (*a*) Simple ideal crystal; (*b*) Distorted crystal; (*c*) (*d*) Cross-sections of perfect and distorted crystals, with constant interfacial angles between prism faces *m*.

A simple type of quartz crystal, illustrated in Fig. 2, *a*, consists of six vertical faces called prisms (*m*), terminated by six inclined faces (*r* and *z*) which together resemble a hexagonal pyramid. Such an ideal form is rare, for crystals generally grow more rapidly in one direction than in another, due to interference by neighbouring crystals or because their food-supply, so to speak, is not equally available in all directions. In consequence, crystals are nearly always more or less distorted in shape, though it is often possible to visualize the appearance of the ideal form. The misshapen crystal of quartz depicted in Fig. 2, *b*, shows an unequal development of the same combination of faces as that of the perfect form. But, as Steno discovered, the angle between adjacent prism faces (*m*) is always 120°, and the angles between the sloping faces are also constant, no matter what shape or size the quartz crystal may be. However much a particular face may be displaced with respect to the centre of the crystal, it always remains parallel to its true orientation.

The extension of Steno's discovery to many other minerals soon led to the formulation of the law of *constancy of interfacial angles*, the most fundamental in the science of crystallography. According to this law the angles between corresponding faces on all crystals of any one mineral species are essentially constant. Every mineral is distinguished by its own individual crystalline form, and in spite of all distortions the angles between pairs of corresponding faces are always exactly the same. In fact, these angles are so characteristic that their measurement affords a valuable means of mineral identification.

Various types of instruments known as *goniometers* (or angle-measurers) have been devised for crystal measurement. For approximate work, especially on large crystals with dull and rough faces, a simple contact goniometer such as that illustrated in Fig. 3 is useful. But, for accurate results, particularly when small crystals with bright faces are available, a reflecting goniometer is indispensable. As a rule, the smaller the crystal the smoother and more flawless are its faces and, when lustrous, thay can be arranged to reflect beams of light from a bright source through a telescope to the eye. By suitably turning the crystal successive reflections from adjacent faces can be directed into the telescope, the amount of rotation necessary to accomplish this being a precise measure of the interfacial angle. Excellent results can often be obtained from crystals less than a millimetre in length.

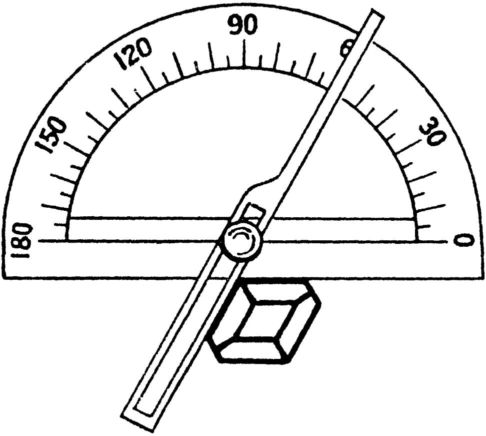


Fig. 3. Contact Goniometer.

Symmetry of Crystals. Even a cursory examination of many crystals reveals a certain regularity in the position of corresponding faces and edges and their symmetrical development enhances the beauty of the minerals. All natural crystals possess some degree of symmetry, which results in the repetition or recurrence of particular faces and edges, the highest degree being shown by cubic crystals, such as those of rock salt. Although the amount of symmetry varies in different minerals it always remains constant for each individual mineral and therefore serves as a natural basis for the classification of minerals into systems or styles of crystal architecture. In order to emphasize clearly the symmetry of a crystal, it must be imagined as freed from distortion and restored to its ideal shape.

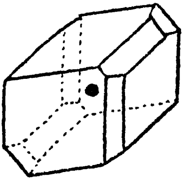


Fig. 4. Axinite Crystal, showing a centre of symmetry, but no planes or axes of symmetry.

Symmetry in crystals is defined with reference to a centre of symmetry, an axis of symmetry, and a plane of symmetry. The possession of a *centre of symmetry* implies the occurrence of parallel faces on opposite sides of a crystal, as shown in Fig. 4, and that every point on the crystal is matched by a similar one equidistant on the other side of the centre. An *axis of symmetry* is an imaginary line passing through the centre of the crystal about which the crystal can be rotated so as to present to the observer the same aspect more than once during a complete revolution. If the repetition of appearance occurs twice during a full rotation, the axis is said to be one of 2-fold symmetry, and its graphical symbol is ●. The only possible types of axial symmetry displayed by crystals are 2- (●), 3- (▲), 4- (■), and 6- (⬢) fold, as depicted in Fig. 5. Finally, a *plane of symmetry* divides a crystal into two halves, each of which is the mirror image of the other. For a homely analogy we may refer to a chair with its single symmetry plane, and to a rectangular table with two such planes at right angles. Some crystals, such as those of common salt and fluorspar, possess as many as nine planes of symmetry, whereas others, including the one shown in Fig. 4, have none at all.

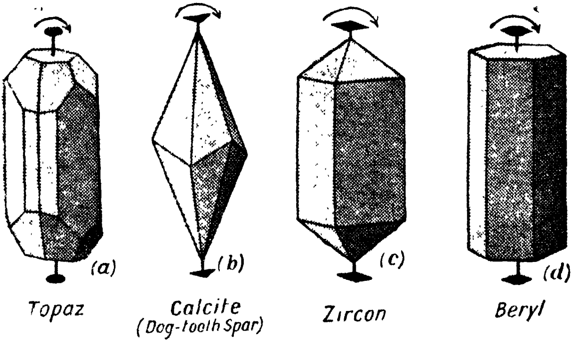


Fig. 5. Crystals with Vertical Axes of (*a*) 2-fold, (*b*) 3-fold, (*c*) 4-fold, and (*d*) 6-fold symmetry.

A crystal of gypsum, Fig. 6, may be taken to illustrate these definitions of symmetry, for it clearly exhibits one symmetry plane, at right angles to which is an axis of 2-fold symmetry, and a centre of symmetry.

The laws that govern crystal structure limit the number of different combinations of the various symmetry elements just described to thirty-two classes. Actually the great majority of minerals are comprised within ten or twelve of these classes. The study of crystals has proved that the thirty-two symmetry classes can be grouped into six *crystal systems* that are defined in terms of certain axes of reference. This broader classification is based upon imaginary lines, called crystallographic axes, which are assumed to pass through the centre of the crystals. In a sense these lines act as a scaffolding upon which the crystal faces are erected. The direction of the axes usually coincides with particular symmetry axes or they may run at right angles to planes of symmetry. Distinction between each of the six great systems depends upon differences in the number, length, and direction of the crystal axes. In five of the systems there are three axes, while the sixth system has four. All crystals, of whatever symmetry, that can be referred to a similar set of axes are included in the same crystal system.

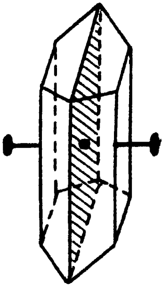


Fig. 6. Gypsum Crystal, showing one plane, one axis, and a centre of symmetry.

Each mineral species has its own characteristic crystal form, which can be assigned to one of the following six systems:

1. Isometric (Cubic): These crystals are referable to three axes, equal in length and at right angles to one another. Some typical forms are the cube, commonly shown by fluorspar and rock salt; the octahedron (Fig. 7, *a*), as in the diamond; and the dodecahedron (Fig. 7, *a*), e.g. garnet.

2. Tetragonal: Includes all crystals which can be referred to three axes at right angles, two equal ones being horizontal and the vertical axis being either longer

or shorter than the other two. A typical form, consisting of a four-sided prism of square section, terminated by four pyramid faces, is that of zircon (Fig. 7, *b*); another example is cassiterite (Fig. 7, *b*), the chief ore-mineral of tin.

3. HEXAGONAL: Contains those crystals that are referable to four axes—three equal horizontal axes intersecting at angles of 120° and a vertical axis of different length. Among the well-known minerals that crystallize in this system are beryl (Fig. 5, *d*), quartz, calcite (Fig. 7, *c*), and corundum.

4. ORTHORHOMBIC: Crystals whose three axes are at right angles to each other, and all of different length. Sulphur (Fig. 7, *d*), topaz, olivine, and barytes are important minerals belonging to this system.

5. MONOCLINIC: Such crystals can be referred to three unequal axes, one being at right angles to the other two, which are themselves inclined to one another at an oblique angle. As representative minerals which crystallize in this system we illustrate orthoclase felspar (Fig. 7, *e*), gypsum (Fig. 6), and hornblende (Fig. 7, *e*).

6. TRICLINIC: Crystals with three axes of unequal length, all intersecting at oblique angles. The very important group of minerals known as the plagioclase felspars, of which albite (Fig. 7, *f*) is a member, belong to this system and axinite (Fig. 7, *f*) is a typical representative.

In each crystal system the class having the highest degree of symmetry is known as the normal class. That of the isometric (cubic) system has nine planes of symmetry, of the tetragonal five, of the hexagonal seven, of the orthorhombic three, of the monoclinic one, and of the triclinic none.

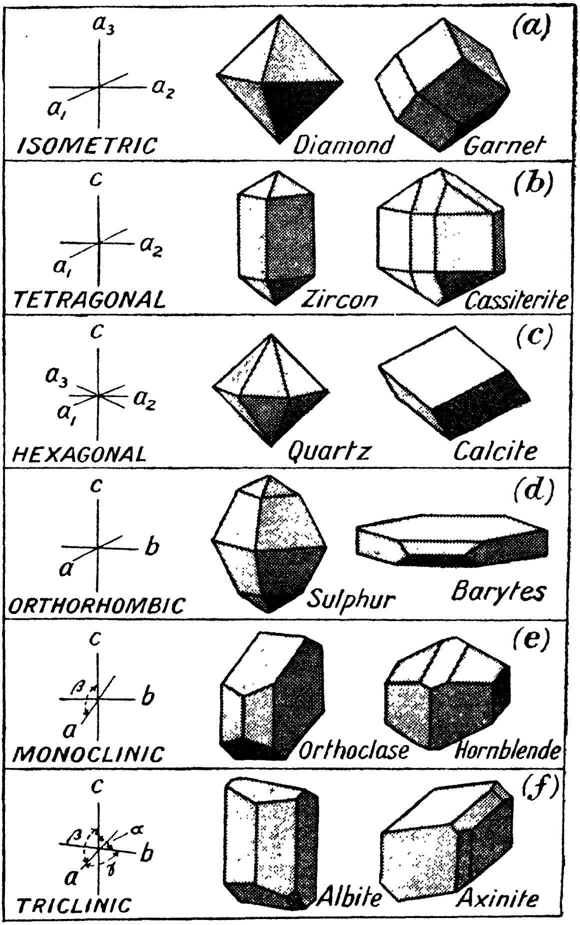


Fig. 7. Crystal Systems.

Whereas in the isometric system the three crystal axes are equal in length, in all the other systems there are axes of different lengths whose relative proportions can seldom be determined simply by measuring the actual dimensions of the crystals. In order to fix the lengths of the crystal axes for any mineral, a face which cuts all three axes is chosen arbitrarily, often because

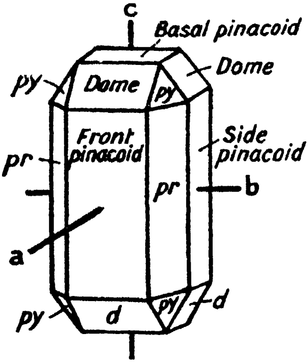


Fig. 8. Olivine Crystal, showing crystal axes and faces in the orthorhombic system; *pr* = prism; *py* = pyramid; *d* = dome.

it is well developed or is parallel to a direction of easy splitting. The ratio of the distances from the centre of the crystal at which this particular face cuts the axes determines the relative lengths of the crystal axes for each individual mineral. This sometimes gives rise to the seeming paradox that when correctly oriented the actual height of the crystal may be its least dimension, despite the fact that its vertical axis is crystallographically the longest. For example, barytes commonly occurs in flat crystals, which appear as shown in Fig. 7, *d*, when oriented in their 'reading position', and yet its vertical crystal axis is the longest one.

In the orthorhombic, monoclinic, and triclinic systems, where the axes are all unequal, a face inclined to all three axes is known as a *pyramid*; faces which cut two lateral axes and are parallel to the vertical axis are called *prisms*; a face which cuts any one axis and is parallel to the other two is a *pinacoid*; and a *dome* intersects one lateral and the vertical axis and is parallel to the other lateral axis. These faces are depicted by a crystal of olivine (Fig. 8). In the tetragonal system the terms pyramid and prisms are used as above; but since the two lateral axes are equal, the term *second order prism* is used in place of pinacoid and *second order pyramid* instead of dome. The names pyramid and prism are also applied in the hexagonal system to faces which cut more than one of the three lateral axes. There are two forms, however, which are confined to this system, namely the *rhombohedron* with six equal diamond-shaped faces, and the *scalenohedron* ('dog-tooth', Fig. 5, *b*) with twelve unequal-sided triangular faces.

Parallel Growth and Twin Crystals. Within rocks the individual crystals are usually grouped together haphazardly and are more or less irregular in outline due to interlocking of the constituent minerals during growth. When the crystal aggregate consists of one mineral it sometimes happens that the individuals are arranged side by side in such a way that their corresponding faces and edges are parallel, as illustrated by the group of quartz crystals shown in Fig. 9, *a*. Such regular aggregates are said to exhibit *parallel growth*, a further example being the so-called drusy crystals of fluorspar consisting of large octahedral crystals coated with minute cubes of the mineral in parallel disposition (Fig. 9, *b*).

The most interesting and important case of regular grouping in crystals occurs when two or more individuals of the same mineral intergrow to form *twin crystals.* Frequently the twin resembles two half crystals united in reversed positions, with a certain crystal plane or direction common to both halves. Although twins normally originate during the actual growth of the crystals, it is convenient in many cases to imagine the twin as a single crystal cut into halves along a plane (the twin-plane), and one half revolved 180° on this plane. A simple instance of this kind is shown by the swallow-tailed twin of gypsum (Fig. 10), which we may visualize as being derived by bisecting a single crystal along the plane indicated by dotted lines, and then rotating one half through 180° on the twin-plane. In this example the surface of union between the two components (called the composition-plane) coincides with the twin-plane, though this is not always so in all types of twinning.

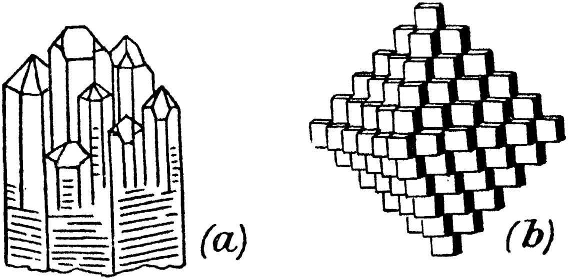


Fig. 9. Parallel Growth. (*a*) Quartz crystals; (*b*) Drusy crystals of Fluorspar.

Two general types of twin crystals can be distinguished, namely *contact twins,* united simply along the composition face, and *penetration twins,* composed of interpenetrating individuals. In addition to twins consisting of two individuals, there are repeated or multiple twins made up of three or more parts. Such twins are known as polysynthetic if their several composition planes are parallel, as in albite (Fig. 11, *b*), and cyclic if they are not parallel and tend to turn in a circle, as in rutile (Fig. 11, *a*). Many twin crystals have the form of a cross or star, and the majority of twins show re-entrant angles, which are absent in untwinned crystals. Care must be taken, however, not to confuse such angles on twins with the re-entrants produced by the fortuitous or parallel intergrowth of separate crystals of the same mineral.

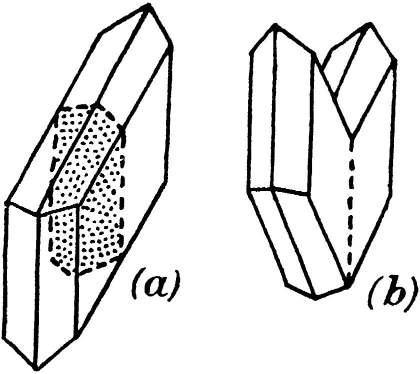


Fig. 10. Gypsum Crystals. (*a*) Simple crystal; (*b*) Swallow-tail twin.

The general tendency of twinning is to develop forms that seem to display a higher grade of symmetry than that of the untwinned crystal. Indeed, some twins are classed as 'mimetic' or 'pseudo-symmetric' twins because they simulate a higher degree of symmetry than they actually possess. For example, the orthorhombic mineral aragonite (calcium carbonate) often assumes a pseudo-hexagonal form as the result of twinning (Fig. 11, *c*).

Twinning that has been induced after the original formation of the crystal, owing to directed pressure or shearing, is referred to as *secondary twinning*. Thus in limestones which have been subjected to pressure the constituent grains of calcite frequently display secondary twin-lamellae, similar to those produced artificially by pressing a knife-blade across the edge of a calcite rhomb (Fig. 12) so as to cause slipping along glide-planes.

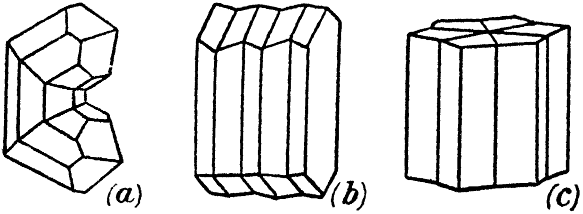


Fig. 11. Examples of Twins. (*a*) Cyclic twin of Rutile; (*b*) Polysynthetic or repeated twin of Albite Felspar; (*c*) Pseudo-hexagonal mimetic twin of Aragonite.

Crystal Habit and Crystalline Aggregates. It is most unusual to find perfect crystals in nature, and the true symmetry of crystals is commonly masked by irregularities of growth and variations in the relative development of the faces. Such variations give rise to *crystal habits,* which are often a characteristic feature of certain minerals. If a pair of opposite faces is much larger than the other faces the crystals are said to be tabular, as in barytes (Fig. 7, *d*, page 31), or lamellar if they consist of superimposed thin sheets, as in mica.

Many minerals are typically elongated in a particular direction and exhibit columnar forms, as in crystals of beryl and tourmaline. If this tendency is accentuated the minerals become needle-like, or acicular, as in many of the zeolites found within the steam-holes of basic lavas. Excessive elongation leads to the development of hair-like or capillary forms, such as those shown by the nickel sulphide, millerite, colloquially known as capillary or hair pyrites. Perhaps the most remarkable of all the stretched-out crystals are the cubes of cuprite, also called ruby copper, which are enormously elongated in the direction of one of their edges; cuprite of this variety, named chalcotrichite, resembles crimson plush when vast numbers of the hair-like crystals are crowded together as a matted aggregate.

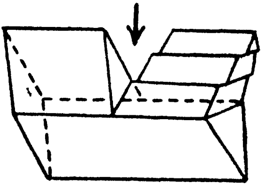
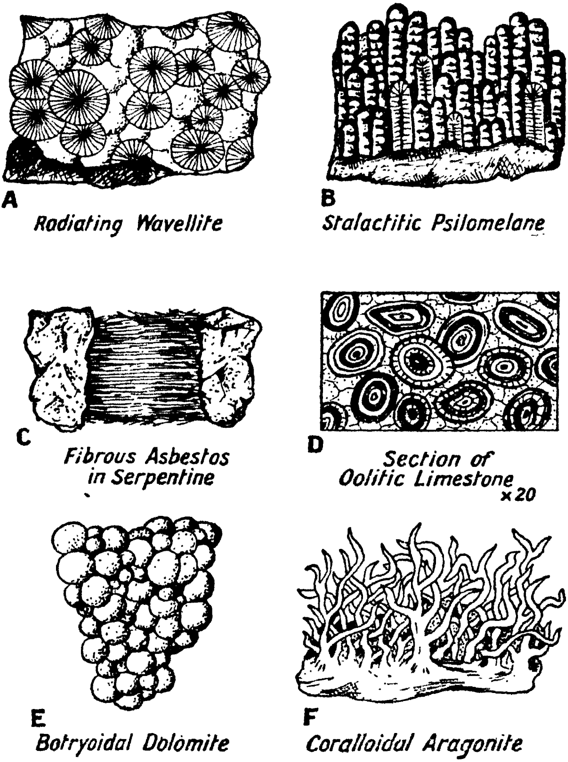


Fig. 12. Artificial Secondary Twinning produced in Calcite by pressure of a knife-blade.

Certain minerals often adopt a characteristic habit which is named in accordance with the predominance of some particular crystal face. For example, the habit may be cubic as in rock salt and fluorspar, octahedral as in diamond and magnetite, rhombohedral as in calcite and dolomite, and pyramidal as in native sulphur.

Most minerals, instead of growing as single well-formed crystals, occur as units in an aggregate of imperfect crystals. Nevertheless, the crowding together of a large number of individual crystals frequently results in the development of special structures and external shapes which are characteristic of certain minerals. Among the many descriptive terms applied to these structures are:



A Radiating Wavellite

B Stalactitic Psilomelane

C Fibrous Asbestos in Serpentine

D Section of Oolitic Limestone ×20

E Botryoidal Dolomite

F Coralloidal Aragonite

Fig. 13. Crystalline Aggregates.

fibrous, consisting of fine thread-like strands, as exemplified by asbestos (Fig. 13, C) and the variety of gypsum known as satin-spar; *columnar*, made up of slender columns, as in hornblende; *lamellar*, composed of thin plates or leaves, as in talc; and *granular*, consisting of an aggregate of large or small grains resembling lump sugar, as in marble.

Moreover, the aggregates often assume curious imitative external shapes and behave as mineral mimics, to which the following descriptive terms are applied: *reniform*, kidney-shaped (e.g. hematite); *botryoidal*, like a bunch of grapes (e.g. dolomite, Fig. 13, E); *mammillary*, with rounded or breast-like surfaces (e.g. malachite); *dendritic*, branching tree-like or moss-like forms (e.g. manganese oxide); *oolitic*, formed of almost spherical grains resembling fish roe (e.g. calcite in oolitic limestone, Fig. 13, D); *stellated*, showing radiating fibres arranged in star-like groups (e.g. wavellite, Fig. 13, A); *wiry* or filiform, in thin wires often bent or twisted (e.g. native silver and copper); *stalactitic* (e.g. psilomelane, Fig. 13, B); and *coralloidal*, like coral, as in the variety of aragonite called *flos ferri* (Fig. 13, F).

During the course of time a mineral may be altered in such a way that its internal structure is destroyed but its external form is inherited by another substance, which thus acts as a mineralogical cuckoo in the nest. A mineral which masquerades in the form of a different species is said to be a *pseudomorph* or false form. For example, a cube of iron pyrites (sulphide of iron) may alter to the 'amorphous' hydrated iron oxide, limonite, which faithfully preserves the external form of the original pyrite and thus provides a pseudomorph of limonite after pyrite. Similarly, the addition of water to the orthorhombic calcium sulphate, anhydrite, may produce a pseudomorph of monoclinic gypsum, and the woody fibre of trees may be gradually replaced by infiltrating silica to form petrified wood. On the plateau of western Colorado many remarkable and valuable petrified logs have been discovered, in which the woody tissue of the trees has been replaced by radium-uranium-vanadium minerals, two exceptional logs being valued at about £50,000. In some cases pseudomorphism may be effected without any change in chemical composition, as when the orthorhombic form of calcium carbonate, aragonite, changes to the rhombohedral form, calcite.

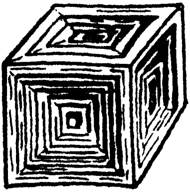


Fig. 14. Hopper Crystal of Rock Salt.

Hurried crystallization induced by the quick cooling of a lava or the rapid evaporation of solutions may result in the development of abnormal forms of crystal growth. Hair-like or plume-like crystal aggregates sometimes form within volcanic glass, and the familiar hopper-shaped crystals of salt (Fig. 14) develop when growth takes place fastest along the edges of the cube.

Among the many odd pranks played by some crystals we may mention twisted crystals of quartz and stibnite (antimony sulphide), sharply folded crystals of gypsum, curved rhombohedra of dolomite and siderite, and the peculiar worm-like forms of chlorite. Certain minerals, notably pyrite, quartz, and tourmaline, are often characterized by deeply striated faces, due to what are known as oscillatory combinations, which result from a rapid alternation of different faces during crystal growth.

Thus, pyrite commonly occurs as cubes, the adjacent faces of which are finely grooved in mutually perpendicular directions due to the repeated alternation of cubic and pyritohedral faces (Fig. 15, *a*). In the case of quartz the horizontal striations (Fig. 15, *b*) are caused by continued and rapid oscillation between the vertical prism face and the inclined rhombohedron (*r*).

During its growth a crystal may accidentally enclose grains of earlier-formed minerals or entrap parts of the liquid from which it is crystallizing. Many transparent crystals, notably those of quartz in granite, contain multitudes of minute cavities with rounded boundaries or with the same shape as the enveloping crystal (then referred to as 'negative crystals'). Quite commonly the cavities are partly or wholly infilled with liquid, and many of them also contain mobile bubbles of water vapour, carbon dioxide, or some other gas which occupy the space created by contraction of the accompanying liquid during cooling of the crystal. Occasionally it is possible to detect microscopic but perfect cubes of rock salt which have crystallized out from the enclosing saturated solution of sodium chloride within the cavity, and it is on record that a remarkable crystal of calcite contained nearly a pint of water trapped within a spacious cavity.

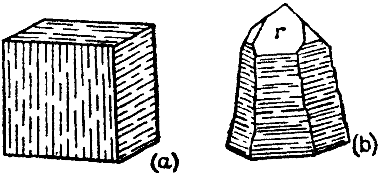


Fig. 15. (*a*) Striated cube of Pyrite; (*b*) Striated crystal of Quartz.

CHAPTER V

THE INTERNAL STRUCTURE OF MINERALS

NEARLY 300 years have passed since Robert Hooke provided the first hint that the regular external form of crystals is related in some way to their orderly internal structure. He demonstrated that by piling spherical musket shot in a systematic manner it was possible to imitate all the shapes exhibited by crystals of alum. Early in the eighteenth century Guglielmini discovered that when certain crystals are split along directions of easy fracture, or 'cleavage', they yield fragments that are essentially identical in shape. Thus crystals of rock salt break easily into cubical cleavage fragments, and calcite splits along three constant directions into small rhombohedra (Fig. 16). Moreover, no matter what the external form of a mineral may be, its cleavage directions remain unchanged. This fact led the Abbé Hauy, the 'father of crystallography', to suggest in 1784 that crystals are built of innumerable minute solid blocks, each having the shape of the elementary cleavage figure, and that the various faces of a crystal result from alternative ways in which the individual blocks are stacked. Hauy's explanation of the shape of a 'dog-tooth' crystal of calcite is illustrated in Fig. 16. The uniform cleavage rhombs are shown stacked closely together. If they are visualized as being extremely small their step-like arrangement becomes imperceptible even under the microscope and the complete crystal appears to have perfectly smooth faces.

With the advent of Dalton's atomic theory, during the opening years of the nineteenth century, Hauy's prescient concept was superseded by the idea that matter consists of groups of atoms joined together to form molecules. Hauy's solid blocks were then replaced by points situated at the various corners, the points representing the position of atoms (or molecules) or the centres of groups of atoms. Such an arrangement of points results in an open three-dimensional network, known as a 'space-lattice', and by linking the points by imaginary lines the lattice can be divided into identical 'unit cells', as depicted in Fig. 17. The particular lattice shown is orthorhombic, since the sides of the cells are unequal and the angles between them are all 90°. It is now known that all crystal faces are parallel to possible planes of the space-lattice, and that the dominant faces are usually

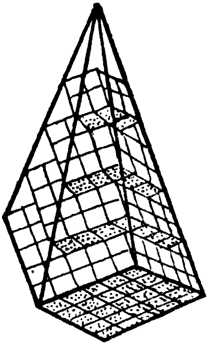


Fig. 16. 'Dog-tooth' Crystal of Calcite, built up of small cleavage rhombs.

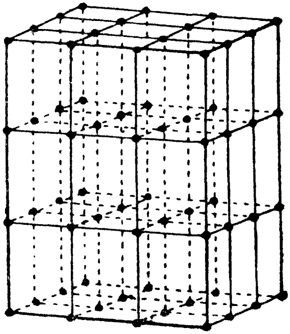


Fig. 17. Orthorhombic Space Lattice.

those containing the greatest number of points (atoms) in a given area.

Each cell in the lattice is a complete unit of pattern, which is repeated again and again in building up the crystal; and each one represents the smallest part of the crystal that possesses the characteristic properties of the complete crystal.

In 1850 the French physicist, Bravais, demonstrated that only fourteen types of space-lattice are possible, their symmetry corresponding to that of the normal classes of the six crystal systems together with that of the rhombohedron. Three of the lattices, shown in Fig. 18, possess isometric (cubic) symmetry. It will be noted that in addition to the simple type with points at the corners of the cube only, there are also lattices in which extra points occur at the centres of the cube ('body-centred') or at the centres of the faces ('face-centred').

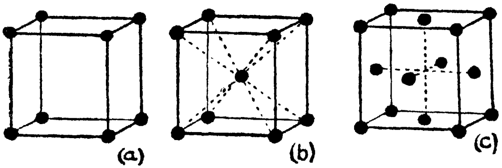


Fig. 18. (*a*) Simple Cubic Lattice; (*b*) Body-centred Cubic Lattice; (*c*) Face-centred Cubic Lattice.

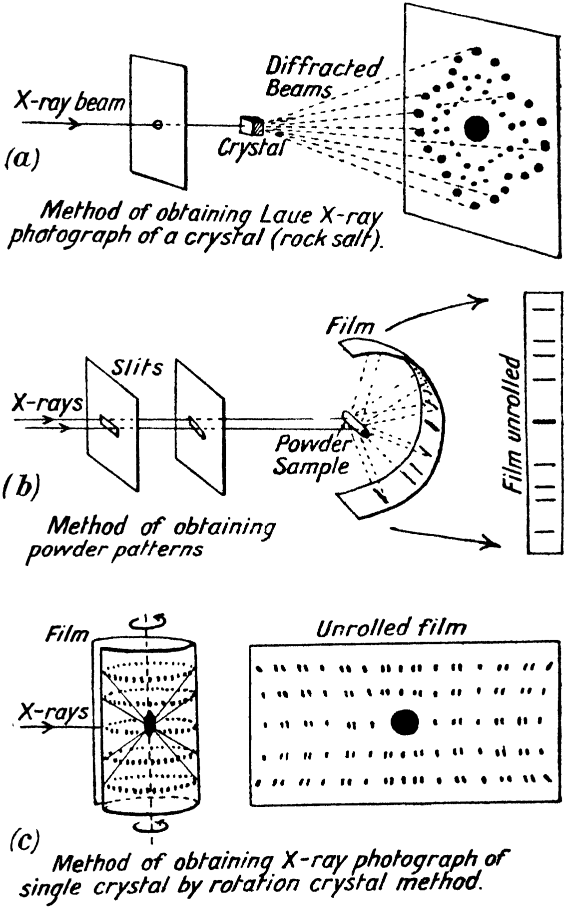
Bravais' geometrical theory of crystal structure was later extended and elaborated, but visible proof of the space-lattice was not forthcoming until 1912, when Laue of Munich, in attempting to determine the nature of X-rays, tried the experiment of passing these penetrative rays through a stationary crystal of zinc blende (sphalerite) and on to a photographic plate. He had conceived the idea that if the wave-lengths of X-rays, which are about 10,000 times shorter than those of visible light, were roughly comparable in magnitude with the spacing between parallel atomic planes in the crystal lattice, then scattering (diffraction) of the rays would result. When developed, the photographic plate revealed a regular geometrical pattern of spots surrounding an intense central spot caused by the direct beam of X-rays. Such 'Laue photographs' (Fig. 19, *a*) are especially useful in determining the symmetry of crystals, which is revealed by the arrangement of the spots. Each spot is due to the reflection of rays in phase by a particular series of parallel atomic planes, and the disposition of the spots is dependent upon the orientation of these planes and, consequently, of possible crystal faces. Moreover, the spots vary in intensity, the darker ones usually representing the commoner crystal faces along which the atoms are most densely packed.

Laue's classical experiment heralded the opening of a new branch of science, that of crystal chemistry, which aims at interpreting the physical and chemical properties of any substance in terms of its crystal structure. It has led to a more profound understanding of the properties of minerals, and to a revised and more scientific mineral classification.

Other methods of employing X-rays in the study of crystal structures were devised soon after Laue's pioneer investigation. In this country in 1913, Sir W. H. Bragg and his son, W. L. Bragg, established for the first time a means of determining the exact spacing of the atomic planes in a crystal of rock salt, by using monochromatic X-rays (predominantly of one wave-length) in conjunction with a gas-filled ionization chamber. Their method yields quantitative results of a high order, but is so laborious that it is now reserved for particularly difficult problems.

Probably the most powerful single method of investigating the structural constants of crystals is the *rotation method*, devised by Schiebold in 1926. A small crystal or crystalline fragment, preferably less than a millimetre across, is placed in a narrow horizontal beam of monochromatic X-rays and is rotated about a vertical axis. The diffracted beams are recorded photographically on a plate or on a cylindrical film, the axis of which coincides with the axis of crystal rotation (Fig. 19, *c*). As the crystal revolves, one series of atomic planes after another comes into the proper position for reflecting the radiation. From the resulting photograph it is possible to calculate the atomic spacing along the axis of rotation, so that by taking three appropriate pictures the dimensions of the unit cell can be determined. Various modifications of the rotation method are now practised, and instead of rotating the crystal through a complete revolution it may be oscillated back and forth through a chosen angle about some principal crystallographic direction.

In the so-called *powder method*, now more widely used than any other, the crystalline material to be examined is crushed to such a fine powder that the minute fragments have a random or chaotic orientation. The powder is either loaded into a capillary tube or moulded with an adhesive into a thin cylinder. A narrow beam of monochromatic X-rays is then directed upon the aggregate, and a diffraction pattern such as that shown in Fig. 19, *b*, is recorded on a cylindrical photographic film. The powdered grains are so numerous that representatives of every atomic plane in the crystalline material are


(a) Method of obtaining Laue X-ray photograph of a crystal (rock salt).

(b) Method of obtaining powder patterns

(c) Method of obtaining X-ray photograph of single crystal by rotation crystal method.

Fig. 19. Derivation of X-ray photographs of minerals.

practically certain to be in the correct position to 'reflect' the X-rays so as to produce characteristic lines on the film. Each line thus corresponds to a definite atomic plane and consequently to a possible crystal face. Moreover, every crystalline mineral yields its own typical arrangement of lines, which provides a 'finger-print' method of identification. In the case of isometric, tetragonal, and hexagonal minerals it is usually simple to determine their internal structures from their respective line patterns, but for other minerals there are considerable difficulties of interpretation to be overcome.

The powder method is especially valuable in identifying fine-grained minerals and grains devoid of crystal faces, and in favourable circumstances even mixtures of minerals can be distinguished and their quantities roughly estimated. For purposes of identification it suffices if the photograph of the unknown mineral can be matched exactly by that of a known species.

Examples of Crystal Analysis. The number of different types of crystal structure among minerals is large, and only a few examples can be mentioned. One of the simplest structures is that of *common salt,* illustrated in Fig. 20. Here the sodium and chlorine atoms (strictly, ions) are arranged alternately at the corners of a set of cubes, the atoms of each kind alone forming a face-centred cubic lattice. Actually the chlorine ion in salt is nearly twice as large as that of sodium, and if we imagine their spheres of influence to be in contact, the internal structure is more accurately represented by Fig. 20, *b.*

The *diamond* structure was one of the first to be investigated. This mineral, composed wholly of carbon, forms crystals belonging to the isometric (cubic) system. Its structure may be described as consisting of carbon atoms located both at the positions of a face-centred cube, represented by black circles in Fig. 21, *a*, and also at the corners of a tetrahedron placed within the cube,

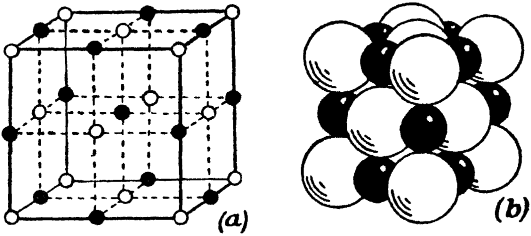


Fig. 20. Common Salt (Sodium Chloride); black circles represent sodium 'atoms' and the hollow ones chlorine 'atoms'.

as shown by the blank circles. Each carbon atom is surrounded by four other carbon atoms situated at the corners of a tetrahedron, and the manner in which they are all linked together is indicated by the dotted lines in the illustration.

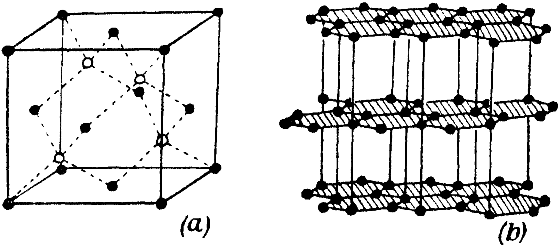


Fig. 21. Structure of (*a*) Diamond, and (*b*) Graphite.

In *graphite*, another crystallized form of carbon, the atoms are arranged in parallel layers, those in each layer forming a hexagonal network, so that the whole structure resembles a honeycomb (Fig. 21, *b*). The distance between atoms in the same layer is less than half the interval between successive layers, parallel to which graphite can be split with great ease. The marked contrast in physical properties between these two forms of carbon, diamond and graphite, is clearly reflected in their widely different internal structures.

During the past thirty years remarkable progress has been made in X-ray analysis, not only of minerals but also of metals, alloys, and hosts of industrial materials, and many fundamental relationships between their internal structure and their physical and chemical properties have now been clearly revealed.

The Nature of Atomic Bonding in Minerals. In common with all other natural objects minerals are composed of one or more of the ninety-two simple chemical substances known as elements, which may be broadly classified into metals and non-metals. The smallest portion of an element that can enter into chemical combination to form a compound is the atom. Why some of the elements are very active in forming compounds whilst a few are inert and refuse to unite with others remained a mystery until about thirty years ago, when the Rutherford-Bohr planetary theory of atomic structure was propounded. This theory pictures the atom as being essentially electrical in construction, consisting of a positively charged heavy nucleus surrounded by a number of revolving negatively charged light particles or electrons. In a sense the tiny universes of the atoms are analogous to the solar system with its planets arranged in orbits around the sun. The atom as a whole is neutral and has no charge, for the number of positive charges on the nucleus is exactly counterbalanced by the number of attendant electrons. Practically the whole mass of the atom lies in the nucleus and the 'atomic number' of an element coincides with the number of planetary electrons surrounding the nucleus. This number increases from 1 in hydrogen to 92 in uranium, each successive element in the continuous series differing in structure from its neighbour by one electron.

The chemical and most of the physical properties of the various elements depend solely on the number and distribution of the external electrons in the individual atoms. These electrons are arranged in rings or orbits around the nucleus according to certain strict rules. Some of the possible arrangements are depicted diagrammatically in Fig. 22. The ring nearest to the nucleus never contains more than two electrons, the next ring no more than eight, the third eighteen and so on. Hydrogen has simply a single electron in the first ring, which is completely filled by the addition of a further electron in the case of helium. In lithium, the third electron must be accommodated in the second ring and, in passing progressively through the elements beryllium, boron, carbon, nitrogen, oxygen, and fluorine, additional electrons are added to this ring until it is finally filled with a complement of eight electrons in the inert gas neon, of atomic number 10. The addition of one more electron calls for a third ring, which becomes progressively filled in passing from sodium to argon, of atomic number 18.

With increase in the number of planetary electrons those in the innermost rings become more and more firmly bound by the attractive force of the nucleus and only the electrons in the outermost orbit are held loosely enough to be disturbed by the energies available in chemical reaction. It is these outer electrons that are directly concerned with chemical changes and their arrangement holds the clue to the formation of most minerals.

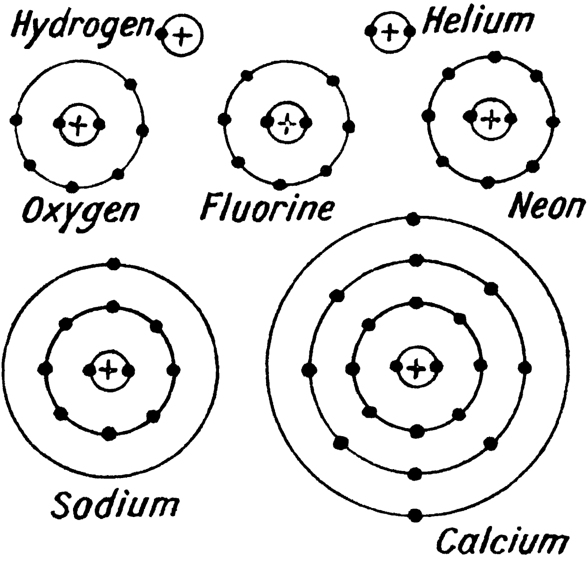


Fig. 22. Electronic Structure of Atoms. Diagram showing grouping of electrons around nucleus.

Every element whose outer ring of electrons is complete is always inert and never formscompounds. Helium, neon, and argon have complete outer rings in their first, second, and third orbits respectively (see Fig. 22). All these three elements are inert gases and their refusal to unite with other atoms reveals the inherent stability of their electronic structure. This stable configuration, however, can be attained by other elements by the loss or gain of one or more outer electrons. An atom with only one or two electrons in its outer ring easily parts with them to achieve stability, whereas an atom whose outer ring is nearly complete readily acquires enough electrons to fill the ring. Metals have few electrons in their outer rings, while non-metals, such as oxygen and chlorine, have nearly complete outer rings.

In the building of minerals there are two principal ways in which the various atoms may combine so as to acquire the stability associated with the inert gases. The vast majority of minerals are formed by the combination of atoms resulting from the transference of one or more electrons from an atom having an excess over the inert gas structure to one with a deficit. This type of bonding is known as *ionic* and the atoms which become charged by this transfer are called ions, respectively positive or negative according to whether the atoms have lost or gained electrons.

Let us examine the diagrams of sodium (Na) and chlorine (Cl), shown in Fig. 23, two elements which combine to form the ionic mineral halite or rock salt, consisting of sodium chloride. We see that the sodium atom has only one electron in its third ring, whereas chlorine has 2, 8, 7 electrons, one less than the stable argon group 2, 8, 8. Chlorine holds tenaciously to its outer seven electrons, while sodium's lone electron in the outer orbit is loosely held. By mutual consent, as it were, the sodium lends its outermost electron to the chlorine atom, both atoms being thereby left with stable configurations. This transfer obviously disturbs the previous electrical balance of each atom; by giving up an electron the sodium atom relinquishes neutrality and becomes a positively charged ion (cation), whilst the acquisition of an electron by chlorine causes it to become a negatively charged ion (anion). Since the two ions thus have unlike charges they attract each other and unite to form a molecule of sodium chloride, NaCl, as represented diagrammatically in Fig. 23.

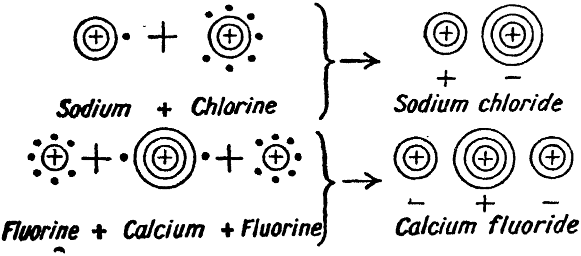


Fig. 23. Diagram showing formation of Sodium Chloride and Calcium Fluoride. Dots represent electrons of the outermost ring; circles indicate rings with full complement of electrons.

The mineral fluorspar, composed of calcium fluoride, which commonly occurs in perfect cubic crystals, affords another simple illustration of an ionic compound. Calcium has twenty electrons arranged 2, 8, 8, 2 and fluorine has nine, disposed 2, 7 (Fig. 23). Mating results in the calcium atom losing its two outer electrons, making it doubly positively charged, and by each of two fluorine atoms gaining a single electron so that both of them become singly charged negative ions. The felicitous union of one calcium and two fluorine atoms thus produces a neutral molecule of calcium fluoride, CaF_2, and in the mineral fluorspar each calcium cation is counterbalanced by two fluorine anions.

Some minerals possess a different type of atomic linkage, known as the *homopolar* or like-ended bond, which results from the sharing of electrons between atoms whose outer rings are incomplete. Thus two hydrogen atoms, each with one electron, may unite to form a hydrogen molecule with the stable structure of the inert gas helium. Similarly in fluorine (2, 7) each atom lacks one electron to achieve the neon structure (2, 8), so that when two fluorine atoms combine by sharing a pair of electrons they form a molecule with the stable configuration of neon, as depicted in Fig. 24.

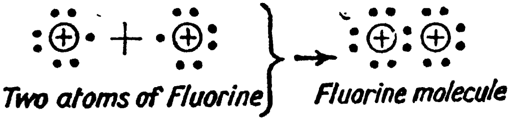


Fig. 24. Diagram illustrating the Homopolar (electron pair) Bond.

A perfect example of such a homopolar structure in minerals is the diamond, composed entirely of carbon atoms. Each of these atoms has six electrons arranged 2, 4 and therefore lacks four electrons to attain the stable neon structure. In the diamond this arrangement is achieved when every individual carbon atom is joined by homopolar bonds to four other carbons, the distance between any pair of linked atoms being the same (see Fig. 21, *a*, page 49).

Finally, a third type of interatomic bond, known as the *metallic* bond, is effected in the case of metals by the removal of electrons from identical atoms, each of which has an excess of electrons. Here the freed electrons behave like a fluid which envelops the aggregate of positive metallic cations and flows as a current under the influence of an electric field. Pure metals are comparatively rare in the mineral kingdom, though locally, native gold, silver, platinum, and copper are sufficiently concentrated to be worth winning.

We may summarize by stating that most minerals have the ionic type of bonding, in which the interatomic binding force consists of an attraction between oppositely charged ions. All the silicates, oxides, carbonates, sulphates, and phosphates are built in this way. The metallic type of bonding is characteristic of the native metallic elements and perhaps of a few sulphides, and among the limited number of homopolar structures are the diamond and certain sulphide minerals.

Importance of Ionic Size in the Building of Minerals. With the exception of the inert gases, such as helium and argon, whose electron rings are complete, every atom is capable of becoming ionized and made chemically active by acquiring an electrical charge as a result of gaining or losing electrons. When two ions approach each other strong repulsive action is suddenly set up when they are a certain distance apart, and closer approach is then prevented. It is thus convenient to picture the ions as spheres, each particular ion having its own characteristic radius. We now realize that in the formation of crystalline minerals the size of the constituent ions and the magnitude of their electrical charges are of paramount importance.

Only those ions which are of an appropriate size can enter the crystal lattice during the growth of a mineral. If two ions have almost the same radius and their charges (i.e. valence) are the same, then either ion can readily take the place of the other in the crystal structure without seriously disturbing its form. Even if ions of compatible size possess unequal charges they are still mutually replaceable, provided the electrical balance of the crystal lattice can be restored by concomitant substitutions among other differently charged ions. Minerals are seldom simple chemical compounds, and the fact that most species vary somewhat in composition is due largely to interchange between different ions of similar size which act as proxy for each other in the crystal structures.

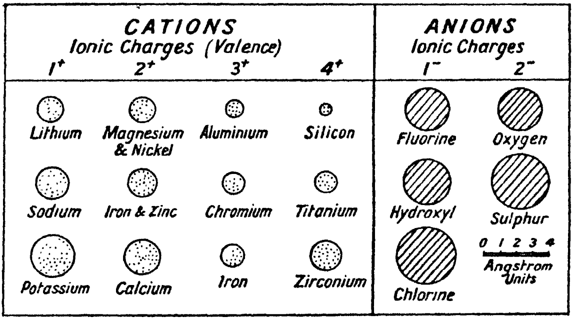


Fig. 25. Relative diameter of selected ions.

The relative size of certain selected ions which commonly occur in rock-forming minerals is listed in Table I, and depicted in Fig. 25.

As the sizes of the various ions are known it is often possible to predict whether any particular element is likely to be present in this or that mineral. For example, since the divalent nickel and magnesium ions have

TABLE I. EFFECTIVE RADII OF SELECTED IONS

Element	*Symbol of Ion*	*Ionic Radius*
Aluminium	Al^{3+}	0·57
Barium	Ba^{2+}	1·43
Calcium	Ca^{2+}	1·06
Carbon	C^{4+}	0·15
Chlorine	Cl^{1-}	1·81
Chromium	Cr^{3+}	0·64
Cobalt	Co^{2+}	0·82
Fluorine	F^{1-}	1·33
Iron	Fe^{2+}	0·83
Iron	Fe^{3+}	0·67
Hydrogen	$(OH)^{1-}$	1·40
Lithium	Li^{1+}	0·78
Magnesium	Mg^{2+}	0·78
Manganese	Mn^{2+}	0·91
Manganese	Mn^{3+}	0·70
Nickel	Ni^{2+}	0·78
Oxygen	O^{2-}	1·32
Potassium	K^{1+}	1·33
Silicon	Si^{4+}	0·39
Sodium	Na^{1+}	0·98
Sulphur	S^{2-}	1·74
Titanium	Ti^{4+}	0·64
Zinc	Zn^{2+}	0·83
Zirconium	Zr^{4+}	0·87

Radii of the ions are measured in angstrom units (10^{-8} cm.). The charges on the ions (valence) are denoted thus: Cations, e.g. Al^{3+}; Anions, e.g. O^{2-}.

practically the same radius, nickel can readily proxy for magnesium in crystals of magnesium silicate without distorting the lattice structure; and in the mineral zinc blende a proportion of the zinc can be replaced by divalent ferrous iron. The close similarity in the sizes of iron and cobalt ions likewise accounts for their frequent intimate association in many minerals. In the case of aluminium-bearing minerals it has been estimated that they all contain about 50 to 100 gm. of the rare element gallium to each ton of aluminium. These two ions possess the same valency and approximately the same radii and are therefore readily interchangeable. These factors also account for the incorporation of rubidium and thallium in potassium-rich minerals, and of the rare element hafnium in zirconium-bearing minerals.

With similarly charged ions of nearly equal size, the smaller ones are preferentially the first to enter the crystal lattice. Thus, in the case of magnesium (Mg^{2+}, 0·78 Å) and iron (Fe^{2+}, 0·83 Å), ions of the former are concentrated in rock-forming minerals during the early stages of crystallization, the amount of iron increasing progressively with falling temperature.

Another significant rule is that if two ions have approximately the same radius but different charges (of the same sign), then the more highly charged ion has prior admittance into the crystal structure. For instance, among minerals rich in divalent magnesium (Mg^{2+}, 0·78 Å), the early formed varieties frequently contain trivalent scandium (Sc^{3+}, 0·83 Å) and the later ones often include much monovalent lithium (Li^{1+}, 0·78 Å). In a similar way the trivalent rare-earth element yttrium (Y^{3+}, 1·06 Å) is commonly found among early calcium-rich minerals (Ca^{2+}, 1·06 Å), the later varieties being often characterized by abundant monovalent sodium (Na^{1+}, 0·98 Å). An outstanding example of the operation of this rule is provided by the felspars, the commonest of all rock-forming minerals, for the calcium varieties (Ca^{2+}, 1·06 Å) normally precede the sodic (Na^{1+}, 0·98 Å) during the course of crystallization, and early crystals of potash felspar (K^{1+}, 1·33 Å) are often notably rich in divalent barium (Ba^{2+}, 1·43 Å).

These few examples may serve to illustrate the fundamental importance of ionic size and the magnitude of their electrostatic charges or valences in regulating the distribution of the elements in minerals, and in controlling the sequence of crystallization among members of the same family of minerals.

The Structure of Silicate Minerals. We have mentioned that the rocks which compose the earth's crust contain in the aggregate about 47 per cent by weight of oxygen, 28 per cent of silicon, and 8 per cent of aluminium.

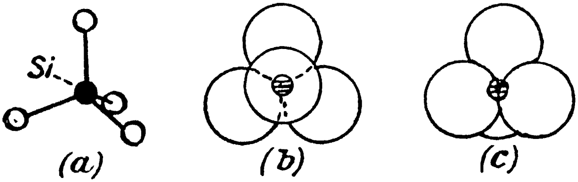


Fig. 26. A Tetrahedral group of Oxygen Atoms around Silicon (SiO_4). In (*a*) the atoms are assumed to be of equal size, so as to clarify their relative positions; in (*b*) and (*c*) the SiO_4 tetrahedron is shown in plan and elevation, the open circles representing oxygen, the small shaded circles silicon atoms, in approximate relative sizes.

Not only is oxygen the most abundant element, but its role in the building of minerals is of paramount importance. The bulky oxygen anions cluster round the cations, such as silicon, aluminium, and iron, grouping themselves as regularly as possible. Moreover, a characteristic number of oxygens surrounds each particular cation; the smaller the cation the fewer in general is the number of enveloping oxygens. Silicon, for instance, is invariably surrounded by four oxygens arranged at the corners of a regular tetrahedron (Fig. 26), whereas magnesium and iron are typically situated at the centre of a group of six oxygens spaced at the corners of an octahedron. Aluminium may form the centre of a tetrahedral group of oxygens, or it may occur within octahedral groups. The large cations, such as sodium, potassium, and calcium, are too big to be fitted in either of the groups just mentioned and are accommodated in roomy, often irregular, cavities in the crystal structure, surrounded by seven to twelve oxygens. In the words of Sir W. L. Bragg, a pioneer in the exploration of the mineral world by X-rays: 'the tetrahedral and octahedral groups are the fundamental units of pattern, the stitches of which the mineral fabric is composed. All the common minerals, however complex their patterns, are a framework of these tetrahedral and octahedral groups'.

Well over 90 per cent of the earth's crust consists of silicate minerals, which comprise nearly 40 per cent of the common minerals and about a quarter of the total number of all the known minerals. They include such well-known species as quartz, felspars, and micas. Investigation of the silicates by means of X-rays has enabled them to be classified into a few clearly defined groups according to the arrangement of silicon and oxygen ions. The fundamental unit of structure of all the silicates is a tetrahedron built up of a silicon ion in the centre and oxygen ions at the four corners. Six principal groups of silicates arise from the different ways in which these SiO_4 tetrahedra are related to each other, for they may exist as independent units or be linked together in various ways. On account of the strong electrostatic forces binding oxygen to the silicon ions the tetrahedral framework constitutes the hardest part of a mineral, and the architectural style of silicate minerals is dominated by the manner in which the linkage of the tetrahedra is effected. The building of these minerals is completed by the inclusion of metallic cations which serve to cement the SiO_4 tetrahedral frameworks together.

The six chief silicate groups are, briefly:

1. *Separate SiO_4 groups*, in which the tetrahedra are not joined directly to each other but are bound together by intervening cations, such as magnesium and iron. Since the SiO_4 group has four excess negative charges, two divalent cations or a single tetravalent cation are necessary to balance or neutralize the structure. Thus minerals such as forsterite, Mg_2SiO_4, and zircon, $ZrSiO_4$, may be developed.

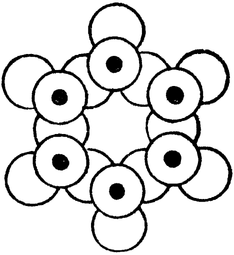


Fig. 27. Si_6O_{18} Ring Lattice; black dots represent silicon, open circles oxygen atoms.

2. *Ring structures*, e.g. Si_6O_{18}, in which the SiO_4 groups are not independent, but are united through common oxygen ions in the form of a ring (Fig. 27). For instance, in the mineral beryl, $Be_3Al_2Si_6O_{18}$, six silicon groups are linked in hexagonal rings which are stacked vertically in honeycomb fashion and bound together laterally by Be^{2+} and Al^{3+} ions.

3. *Single Chain structures*, Si_2O_6, formed by linking the tetrahedra corner to corner in an endless chain, each tetrahedron sharing an oxygen with its neighbour (Fig. 28, *a*). Such a chain structure is characteristic of the pyroxene group of minerals, including enstatite, $MgSiO_3$, and diopside, $CaMgSi_2O_6$. The strong chains are arranged parallel to the vertical axis of the minerals and are bound together sideways by metallic cations.

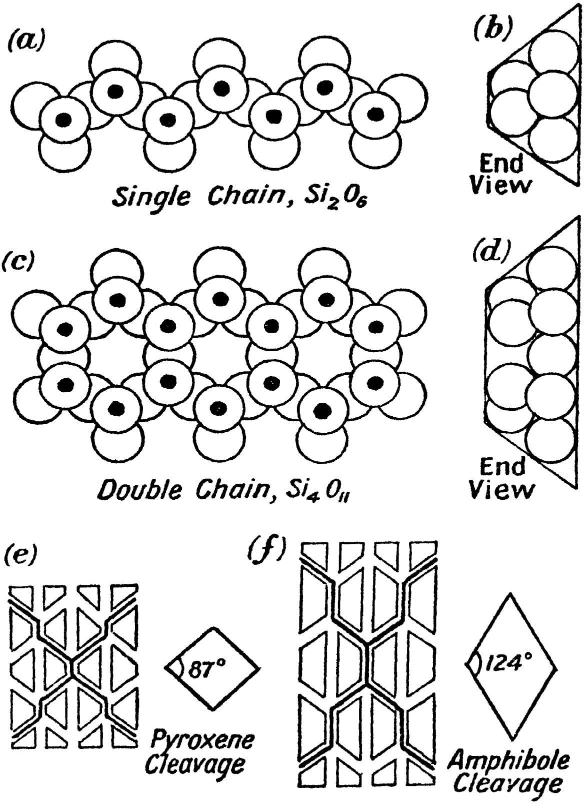


Fig. 28. Silicate Lattices in Pyroxenes and Amphiboles. Black dots represent silicon, open circles oxygen atoms. (*a*) Single chain structure, Si_2O_6, characteristic of pyroxenes; (*b*) Single chain, end view; (*c*) Double chain structure, Si_4O_{11}, characteristic of amphiboles; (*d*) Double chain, end view; (*e*) and (*f*) Stacking of single and double chains respectively, with resulting cleavage directions, shown by heavier lines.

Splitting or cleavage directions in these minerals lie between the chains, as illustrated in Fig. 28, *e*, intersecting almost at right angles.

4. *Double Chain structures*, Si_4O_{11}, in which two single chains are joined together side by side, giving a silicon: oxygen ratio of 4 : 11 (Fig. 28, *c*). Double chains of this type are characteristic of the various amphiboles, including tremolite, $Ca_2Mg_5(Si_4O_{11})_2(OH)_2$, the chains being alined parallel to the vertical axis of the minerals and linked laterally by cations. Cleavage directions again avoid cutting through the chains, as shown by the heavy lines in Fig. 28, *f*, and intersect at 124°.

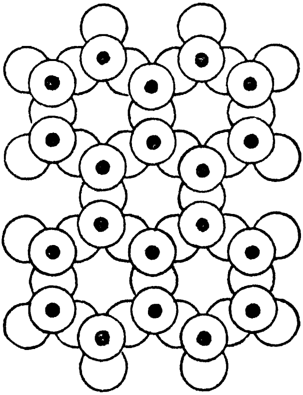


Fig. 29. Sheet Lattice, Si_4O_{10}. Black dots represent silicon, open circles oxygen atoms.

5. *Sheet structures*, Si_4O_{10}, arise when the tetrahedra are joined to neighbours by three corners and extend indefinitely in one plane as a hexagonal network (Fig. 29). This arrangement is typical of the micas and other flaky

minerals such as talc, $Mg_3Si_4O_{10}(OH)_2$, and the so-called clay minerals, and is directly responsible for their pseudo-hexagonal symmetry and for the highly perfect cleavage which runs parallel to the sheets. The individual tetrahedral sheets are piled one above another and are cemented together by metallic ions and (OH)-groups.

6. *Three-dimensional frameworks*, SiO_2, in which each tetrahedron is linked to its neighbour by all four corners, so that every oxygen is common to two tetrahedra. The various forms of silica, SiO_2 (e.g. quartz), are of this type, the tetrahedra consisting solely of silicon and oxygen ions. In this particular case the valency rule is satisfied, for the positive charges on silicon are exactly balanced by the negative charges on oxygen. In many minerals, however, trivalent aluminium replaces tetravalent silicon within the tetrahedral groups, so that they become negatively charged and must be neutralized as regards valency by the incorporation of metallic cations. Thus, if one quarter of the silicon ions are replaced by aluminium the radicle SiO_2 (which may be written Si_4O_8) becomes $AlSi_3O_8$, with a negative valence of one, which is satisfied by the incoming of potassium, as in orthoclase felspar, $KAlSi_3O_8$, or by sodium, as in albite felspar, $NaAlSi_3O_8$. If half the silicons are exchanged for aluminium the radical then becomes $Al_2Si_2O_8$, and the resultant two negative charges may be balanced by divalent calcium, as in anorthite felspar, $CaAl_2Si_2O_8$. The large cations potassium, sodium, and calcium are conveniently accommodated in the open spaces within the tetrahedral frameworks.

Not only may silicon be replaced by aluminium in the various types of framework, but among the cementing cations aluminium may be exchanged for ferric iron, magnesium for ferrous iron, nickel for lithium, calcium for sodium, potassium for barium, etc., the changes being reflected by concomitant variations in the physical properties of the minerals.

The passage from the comparatively simple structures associated with separate SiO_4 tetrahedra to those of three-dimensional frameworks usually involves an increasing complexity and a looser packing of the mineral fabric, and is in general accompanied by decreasing density and diminishing refractive index of the silicate minerals. Moreover, minerals of simple structure, such as olivine $(Mg,Fe)_2SiO_4$, tend to crystallize out from molten magma at higher temperatures, and as cooling proceeds they are followed by silicates of successively more complex pattern, quartz (SiO_2) being one of the latest to form.

CHAPTER VI

THE PHYSICAL CHARACTER OF MINERALS

THE NATURE and arrangement of the atoms in a mineral determine not only its crystalline form but also its physical characters, such as hardness, density, optical properties, and ability to cleave in particular directions. These characters are of the utmost importance in the identification of minerals, for they usually enable us to recognize most of the common species at sight or by means of simple tests. Only a few of the many physical characters of minerals can be singled out for description here.

Colour is one of the most attractive characters of a mineral and usually the first to be observed. For many minerals, especially those of metallic appearance, colour is of great diagnostic value, but in many cases it is not a constant and reliable feature and must therefore be used with caution. The blue of azurite and green of malachite (carbonates of copper), the pale brass-yellow of pyrite (iron sulphide), and the red of copper and cinnabar (mercury sulphide) are examples in which the colour of the minerals on fresh surfaces is 'idiochromatic', for the colouring is an inherent property due to the essential presence of a pigmenting element. On the other hand, 'allochromatic' minerals may display a bewildering variety of non-essential colours which result from the presence of colouring matter in the form of impurities or inclusions. Thus, fluorspar can be colourless, green, yellow, white, rose pink, blue, brown, or purple as in Derbyshire 'Blue John', and a single crystal may show bands of different colour or be tinted in irregular patches. Quartz exhibits a similar wide range of colour, its varieties including colourless pellucid rock crystal, violet amethyst, golden yellow citrine, red jasper, and rose quartz.

The colour displayed by a mineral depends upon the nature of the light which it absorbs or reflects. A white mineral reflects or transmits all colours of the spectrum equally, a red one absorbs all colours except those which together produce the sensation of red, and a black one absorbs the whole range of spectrum colours. The '*body colour*' or 'transmission colour' of a mineral is thus due to selective absorption of the light which enters it. A cubic mineral normally shows the same tint for a particular thickness in whatever direction it is viewed, the colour being independent of the direction of propagation of the light. A coloured mineral belonging to any other crystal system, however, may appear variously coloured when seen by transmitted light in different directions, owing to differences in selective absorption as the light travels along alternative paths. For example, tourmaline may be almost black when examined in one direction, whereas across this direction it may be brown or green; and the gem-stone cordierite, or water-sapphire, is dark violet, clear blue, or straw-yellow when viewed in three different directions at right angles.

Chemical composition has a profound effect upon the colour of minerals, which is commonly due to an intrinsic property of the atoms or ions. It is impossible to differentiate clearly between coloured and colourless elements, for some elements form both coloured and colourless ions and others, which are colourless in one state of valency, exhibit strong colour in another. We can say, however, that among the colourless ions are those of aluminium, sodium, potassium, calcium, magnesium, and barium, and that coloured ions are those of the so-called transition elements, including titanium, vanadium, chromium, manganese, iron, cobalt, nickel, and copper (atomic numbers 22 to 29). The position which an ion occupies in the crystal lattice is of great importance in connexion with colour, for the light absorption of an ion depends partly upon its surroundings. Thus, the pink cobalt ion is surrounded by six oxygens, whereas the blue one has four. Different states of valency or ionic charge of an element also result in variations in colour. In its ferrous condition iron is sometimes responsible for green coloration, whereas in the ferric state, iron often creates a yellow, brown, or red colour, and the simultaneous presence of ferrous and ferric ions frequently produces a deep shade of blue or green. Iron is undoubtedly the chief pigment in the colour-box of nature, and the varying ratio of ferrous to ferric iron in minerals is accompanied by concomitant changes in their body colour.

Among the gem-stones the deep red of spinel and true ruby, and the green of emerald, may be ascribed to the presence of small quantities of chromium. The crimson of certain garnets and the red of carnelian is due to ferric iron; the purple of amethyst is attributable to traces of trivalent manganese, the green of amazonstone possibly to rubidium, and the blue of sapphire—a precious form of corundum—is due to minute amounts of titanium. When pure the mineral zinc blende or sphalerite may be almost white, but with progressive replacement of its zinc by iron it changes through yellow to brown and then finally to black when the content of iron reaches about 15 per cent. In two of the most abundant silicate groups, the pyroxenes and amphiboles, the calcium and magnesium varieties are virtually white, but with increasing amounts of iron they range in colour from green to black.

It is generally admitted that the colour of minerals is primarily due to a field of force, chemical or electrical in nature, which is not completely saturated or balanced. Strong and uniform binding forces between the atoms favour the transmission of light, whereas unsaturated valencies or feeble bonds favour the absorption of light and cause a deepening of colour. Two carbon minerals, diamond and graphite, illustrate this fact. The diamond is usually colourless owing to the strong linkage between all its carbon atoms and the highly symmetrical electrostatic forces within its lattice; graphite, on the other hand, is black because the bonds between its carbon atoms are not of uniform strength, the links between successive parallel sheets (Fig. 21, *b*, page 49) being weak in comparison with the firm interlinkage between carbons lying within the same sheet. It is true that many diamonds are dark, but this is generally due to slight imperfections in the crystal lattice, though minute impurities may also cause discoloration.

Minerals possessing intense absorption are said to show *surface colour*, which is due to the reflection of light of certain wave-lengths from their surface. Such minerals reveal a different colour by reflected light from that seen by transmitted light. Typical minerals exhibiting distinct surface colour are the native metals such as gold, silver, and copper, together with many oxides and sulphides which display marked metallic lustre, including magnetite (Fe_3O_4), pyrite (FeS_2), and galena (PbS). Thin films of silver are blue in transmitted light, and goldleaf appears green or, when thin enough, even blue. It is interesting to note that as the pale-coloured native metals are ground more and more finely their powders tend to become black, whereas the continued crushing of transparent coloured minerals eventually yields an almost white powder.

Apart from the colouring directly related to chemical composition, many minerals exhibit colours due to peculiarities in their physical structure. In this case, owing to the presence of lamellar inclusions, thin films, or minute particles often of colloidal dimensions, the incident light is selectively refracted, scattered, or otherwise changed in direction of propagation so as to produce colours. For instance, partial reflection of light from the upper and lower surfaces of parallel microscopic platy inclusions accounts for the iridescent *play of colours* shown by the felspar, labradorite. On turning the mineral it suddenly flashes with the brilliant metallic colours of a peacock's feather, but on further rotation the felspar resumes its normal dull grey tone. Some minerals, notably the hydrated iron oxide, limonite, display bright iridescent colours due to a thin surface film or coating, and the same effect may be produced in other minerals by reflection from internal fractures or cleavage cracks. When freshly broken surfaces of certain minerals, including the copper-iron sulphides, chalcopyrite and bornite, have been exposed to the atmosphere, they may rapidly acquire quite different colours due to a *tarnish* caused by thin oxidized films.

The rapid and beautiful change of colours shown by precious opal in reflected light is generally attributed to the interference of rays at the surface of fine cracks infilled with opaline material having a slightly different index of refraction to that of the surrounding opal, probably on account of unequal water content. These spectacular colours are not essential properties of the mineral, for if it is viewed by transmitted light it looks like common opal, milky or pale yellowish and translucent. Incidentally, certain opaque opals exhibit prismatic colours when immersed in water, after the liquid has penetrated into the minute cracks in the stone.

In mother-of-pearl or nacre, the iridescence is due largely to interference of light in the thin overlapping layers of calcium carbonate (aragonite) which line the inside of the shell.

Moonstone, so called because of its bluish moon-like opalescence, is a potash felspar containing microscopic parallel lamellae of the soda felspar, albite. It owes its attractive colour to the reflection of light from these minute inclusions which have segregated from the host felspar during its cooling history. Another felspar, oligoclase, is called sunstone when it contains abundant delicate flakes of the reddish iron oxide, hematite, which impart a golden shimmer and sparkle to the mineral. Colouring in certain minerals has recently been attributed to the inclusion within them of minute particles of colloid dimensions which cause scattering of the incident light, the resulting colour varying with the particle size. Investigations have shown that the translucent blue, pink, and reddish-brown tints of rock salt and celestite ($SrSO_4$) may be due to the presence of traces of colloidal gold.

Although a mineral may display a wide range of colour due to the presence of pigmental impurities, the colour of its fine powder, known as its *streak*, is practically constant. This essential property, which is of considerable diagnostic value, can be conveniently determined by crushing the mineral on a sheet of white paper or by rubbing it on a piece of white unglazed porcelain. The streak may have the same colour as the mineral in mass, but it is often quite different. Moreover, minerals whose mass colour is practically identical may have dissimilar streaks. For example, the three iron minerals hematite, limonite, and magnetite may all appear blackish, but their respective streaks are always red, yellow-brown, and black.

The native metals and most of the metallic sulphides are *opaque*, for they do not transmit any light even on the thinnest edges. On the other hand, many minerals, such as rock crystal (quartz) are so *transparent* that objects can be seen through them distinctly. Intermediate between these two extremes are the *translucent* minerals, including chalcedony, onyx, and jade, which transmit light but do not allow objects to be seen through them.

A property of great importance in the recognition of minerals is the *lustre* of their surfaces in reflected light. Opaque minerals, such as gold, pyrite, and galena, which possess the brilliant appearance of a metal, are said to have a metallic lustre. All other kinds of lustre are classed as non-metallic, and include such descriptive types as vitreous or glassy (e.g. quartz), resinous (zinc blende), silky (fibrous gypsum or 'satin spar'), waxy (chalcedony), adamantine (brilliant diamond), and dull or earthy (chalk and china clay).

Some specimens of fluorspar have the remarkable property of appearing pale green when viewed by transmitted daylight and a plum-blue or bluish-violet colour by reflected light. This phenomenon, first recognized in fluorspar, is known as *fluorescence*, and is most spectacular when the mineral is exposed to ultra-violet radiation, X-rays, or cathode rays. Fluorescent minerals absorb these invisible rays and transform them into visible light of a longer wave-length. Probably all fluorescent minerals are also *phosphorescent*, for they continue to glow after the exciting rays are cut off, though in many cases the after-glow persists only for a small fraction of a second.

Fluorescence is usually produced by excitation with ultra-violet radiation, which may be conveniently divided into two regions, known as long-wave U.V. and short-wave U.V. (Fig. 30). For practical purposes the effective short-wave range lies between 3,000 and 1,800 A.U. When testing the fluorescence of minerals the most convenient source of ultra-voilet light is the mercury-vapour lamp. Certain minerals are excited by long-wave, some by short-wave, and others by both. Most fluorescent minerals exhibit only slight colour variation throughout the whole range of U.V. radiation, but in many specimens the colour emitted during fluorescence varies with the wave-length of the ultra-violet rays. For instance, some calcites glow with a blue light for short-wave and pink for long-wave radiation, and the tungsten

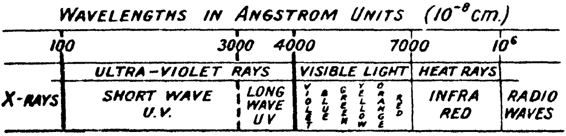


Fig. 30. Part of the Radiation Spectrum.

mineral, scheelite ($CaWO_4$), normally fluoresces bright blue in short-wave but responds only very feebly to long-wave U.V. Again, particular minerals may only fluoresce for a certain limited range of U.V. radiation.

It must be emphasized that, apparently with rare exceptions, fluorescence is not a constant physical character of any specific mineral, and it is seldom exhibited by pure specimens. The phenomenon is almost invariably due to the fortuitous inclusion within the mineral of a metal impurity, such as manganese or copper, known as an activator. For this reason a U.V. lamp is not an infallible means of mineral diagnosis, except in the case of scheelite. Even fluorspar itself does not always display the phenomenon. Nevertheless, in certain localities particular minerals are so commonly fluorescent that the lamp can be employed as a fairly reliable detector. Thus, at the Franklin Furnace mine, New Jersey, the zinc mineral willemite nearly always gives a vivid yellowish-green fluorescence, which serves as a means of sampling ore specimens and of determining the amount of willemite present in the mill tailings. Other minerals which often, but by no means invariably, fluoresce are aragonite, diamond, and zinc blende, whilst several uranium minerals, especially the phosphate (autunite), glow with a brilliant yellow-green colour. The presence of mercury in a substance can be readily detected on heating because its vapour absorbs short-wave radiation and casts dense black shadows on a fluorescent screen.

In the United States, Canada, and elsewhere portable U.V. lamps have been widely used within recent years in locating scheelite deposits and for examining underground workings in tungsten mines. During surface prospecting, trenches opened up along the outcrop of scheelite-bearing veins are scrutinized at night or beneath a tarpaulin cover with the aid of a short-wave U.V. lamp. At Mill City, Nevada, the bluish fluorescence of scheelite is turned to advantage in examining the tailings of concentrating plants and for showing up the mineral on picking belts. Incidentally, it is now known that the fluorescence of scheelite changes from blue to yellow as its deleterious content of molybdenum increases.

Fluorescence in minerals results when radiations of relatively low energy, such as U.V. light, impinge on metallic impurities (activators), causing a momentary transfer of electrons from lower to higher energy levels or to orbits farther removed from the atomic nuclei. An unstable condition is thus created, and after excitation the electrons revert almost instantaneously to their original level, releasing surplus energy in the form of visible light. In the case of phosphorescence the energy of excitation appears to be stored, the displaced electrons being temporarily frozen and subsequently released relatively slowly by thermal agitation or otherwise, with the continued emission of visible light.

Only brief reference can be made to the *refractive power* of minerals. When light passes from air into a mineral it is bent, or refracted, from its original path and its velocity is retarded. The amount of refraction is directly proportional to the ratio between the speed of light in air and in the mineral. If the velocity of light in air is taken as unity, then the refractive index of a mineral is inversely proportional to the speed of light travelling through it. Thus, if the index of refraction of a mineral is 2·0, light passes through it with half the velocity it has in air. Each mineral has its own characteristic refractive index, the determination of which affords an accurate and ready means of identification. Examples of such indices are: water 1·33, fluorspar 1·43, crown glass 1·53, garnet (almandine) 1·78, and diamond 2·42.

Every mineral has different refractive indices for light of different colour, the refractive index for red light being less than that for blue, and it is usual to adopt as the standard the yellow light of a sodium flame. Variation in refraction for different colours, known as *dispersion*, accounts for the splendour of the rainbow and the 'fire' of a faceted diamond. This highly prized attribute of the diamond is due to its extraordinary power of splitting up white light so that its component colours are widely dispersed, the index of refraction for red light being 2·407 and for violet light 2·465. A brilliant-cut stone is so fashioned that slight movements of the diamond produce scintillating flashes of pure rainbow colours (Fig. 31). In common with many other gem-stones of high refractive index the diamond possesses a characteristic and brilliant adamantine lustre. Substances like glass or quartz, which have a relatively low dispersion

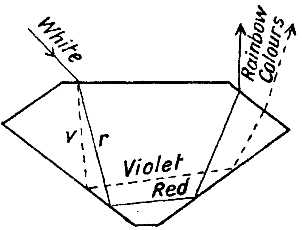


Fig. 31. Colour-dispersion in a brilliant-cut Diamond.

and index of refraction, show little or no fire and lack the sparkling lustre of highly refractive minerals.

In amorphous minerals, such as opal, and in minerals belonging to the cubic system, the refractive index is the same whatever the direction of the incident light and its passage through the substance. Such minerals are said to be *isotropic*, or *singly refracting*, since a ray of light entering them travels on as a single beam, although bent from its original course. On the other hand, when an ordinary ray of light passes into any crystalline material not belonging to the cubic system it is, in general, split up into two rays which vibrate in planes at right angles to one another, as 'plane polarized' rays. Each ray travels through the mineral with a characteristic velocity and has its own separate refractive index. Since the angle of refraction differs for the two rays, such minerals are said to exhibit *double refraction*. This phenomenon is best displayed by the transparent rhombs of calcite known as 'Iceland spar'. If a circle or cross drawn on a sheet of paper is viewed through such a clear rhomb, double images appear, as shown in Fig. 32, *a*. But when the mark is observed through the rhomb in one particular direction, namely along the vertical axis of the crystal, only a single image is seen. This direction is called the optic axis, along which light travels without being doubly refracted. Minerals crystallizing in the tetragonal and hexagonal systems have one optic axis only and are therefore classed as *uniaxial*, their double refraction increasing to a maximum when light enters them at right angles to this unique axis. Orthorhombic, monoclinic, and triclinic minerals possess two optic axes and are consequently referred to as being *biaxial*.

Examination of the optical properties of minerals in grains and in very thin sections under the microscope, especially with the aid of polarized light, constitutes a fundamental branch of mineralogy and is of cardinal importance in the detailed study and classification of rocks. For the microscopic investigation of minerals and rocks, they are usually smoothed on one side and cemented to a glass slip by means of Canada Balsam, a gum which hardens on heating. The substances are then ground down with appropriate abrasives to the required thinness, normally about 30 microns (or $\frac{1}{30}$ mm.), and covered with a thin glass slip fixed with balsam. The finished thin section is then ready for examination by transmitted light, a procedure which affords precise diagnostic information concerning many of the optical characters of the minerals, including their refractive indices and the strength of their double refraction.

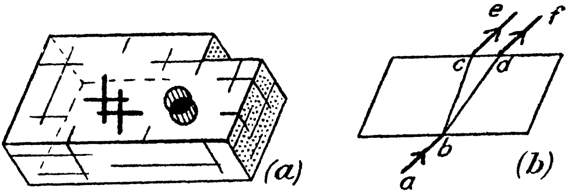


Fig. 32. Double Refraction in Calcite. (*a*) A single cross and circle viewed through calcite; (*b*) Single ray *ab* split into two rays, *bc*, *bd* in passing through calcite, emerges as rays *ce*, *df*.

Opaque minerals are best examined by reflected light after their surfaces have been ground and thoroughly polished. Using an ore-microscope, ordinary light or polarized light is reflected vertically downwards on to the surface of the opaque minerals, from which it is reflected to the observer's eye. With this instrument it is possible to determine whether an ore-mineral belongs to the cubic system or not, to ascertain its degree of reflectivity, and to decide whether it crystallized earlier or later than the accompanying minerals. Valuable diagnostic criteria can also be gained by observing under the microscope the effect of etching the polished surfaces with various reagents, and of scratching them with a needle. Further consideration of the optical properties of minerals in thin and polished sections is beyond the scope of this book, and the interested reader is therefore referred to volumes of a more specialized kind.

In its strongly *magnetic* character the black iron oxide, magnetite (Fe_3O_4), is outstanding among minerals for it is readily attracted by even a weak hand magnet, and its presence in deeply buried rocks can be detected by magnetometers. Moreover, certain specimens exhibit polarity, so that one part attracts and an opposite part repels the north pole of a compass-needle, and if freely suspended they behave as natural magnets which aline themselves in a north-south direction under the influence of the earth's magnetic field. Such specimens, known as lodestones, probably derive their polarity from a concentration of the earth's field at the ends of magnetite orebodies or from the effects of repeated discharges of lightning. The iron sulphide pyrrhotite, or 'magnetic pyrites', is also strongly magnetic though to a much lesser degree than magnetite. Geophysical methods of locating concealed nickel deposits are often facilitated by the presence in them of abundant pyrrhotite, which can be readily detected by magnetic instruments.

Between the poles of a powerful electromagnet the *paramagnetic* minerals are attracted and the *diamagnetic* ones are repelled. For example, all compounds of iron, including hematite, siderite, ilmenite, chromite, and wolfram, are paramagnetic, whereas calcite and zircon are typical diamagnetic minerals. This variation in the magnetic susceptibility of different minerals is turned to account in the electromagnetic separation of minerals, an important industrial ore-dressing process. By varying the strength of the electromagnet, minerals of differing susceptibility can be separated from each other, as, for example, magnetite from apatite, wolfram from tinstone, monazite (cerium phosphate) from garnet and rutile, and chromite from its associated silicates.

Minerals with a metallic lustre, including the native metals, graphite, sulphides (except zinc blende), and certain oxides, are good *conductors of electricity*, though the great majority of minerals are very poor conductors. A simple laboratory method of separating conductive minerals is by means of a glass rod in which a positive electrostatic charge is induced by rubbing with silk, or by using a stick of ebony or sealing-wax which has been negatively charged by rubbing with catskin. In commercial practice one process of electrostatic separation involves the dropping of finely crushed ore on to a rotating electrified cylinder. Conducting particles become charged by induction and are vigorously repelled from the drum whilst the free fall of bad conductors is relatively unaffected. A shower of pulverized ore can thus be separated into distinct fractions. In this way, for example, the poor conductor zinc blende can be separated from good conductors such as galena and pyrite.

Certain minerals become electrically charged when suitably heated or cooled, and are said to exhibit *pyroelectricity*. This curious phenomenon is shown only by crystals which lack a centre of symmetry and possess polar axes of symmetry whose two ends are associated with dissimilar faces. It was first observed in crystals of tourmaline (Fig. 33) which, on being heated, acquire a negative charge at the acute end and a positive one at the obtuse end. This can be demonstrated vividly by blowing a mixture of finely powdered red lead and sulphur through a muslin sieve and on to the heated crystal. In passing through the sieve the particles become electrified by mutual friction, the positively charged red lead being attracted to the negatively electrified end of the crystal and the yellow sulphur to the positively charged end. The vertical axis of the tourmaline, which is polar in character, is termed its 'electric axis'. In the case of quartz, heating produces positive and negative charges at opposite ends of its three horizontal axes, each of which is an electric axis, so that under the lead-sulphur spray the vertical edges of the mineral become coloured either with red or yellow dust.

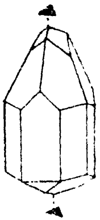
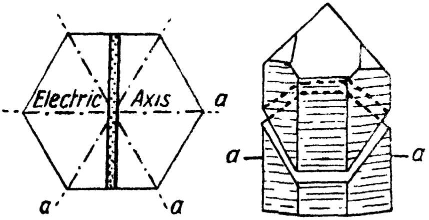


Fig. 33. Tourmaline Crystal with vertical polar axis of symmetry.

Electric charges may be developed on crystals devoid of a centre of symmetry not only by heat but also by suitably directed pressure. This phenomenon, known as *piezoelectricity*, is, like pyroelectricity, most marked along the polar or electric axes. Thus pressure directed along the vertical axis of tourmaline induces positive and negative charges at opposite ends of the crystal. Plates cut at right angles to the length of the mineral are so responsive to even slight variations of pressure that they may be utilized in precise recording instruments, such as depth-sounding apparatus. Quartz is the outstanding piezoelectric mineral, for properly oriented sections or plates are now extensively used as resonators (oscillator-plates) for frequency control in radio and telephone communication systems. Literally scores of millions of quartz oscillator-plates, resembling small microscope cover glasses, have been manufactured since 1941 for use in a great variety of radio sets for the Services, and nearly all broadcasting or other radio stations are now held to their assigned frequency by quartz control.



(*a*) (*b*)

Fig. 34. Piezoelectric Quartz Crystals. (*a*) Plan showing an 'X' cut; (*b*) elevation showing a 'BT' cut.

Satisfactory plates may be sliced through a crystal of quartz parallel to its length and perpendicular to a horizontal electric axis. These are known as 'X' cuts (Fig. 34, *a*). Better results are obtained, however, by cutting the plates parallel to an electric axis but on an incline, as in the 'BT' cut (Fig. 34, *b*). Such plates become mechanically deformed when subjected to an electical field and, depending upon their thickness, they can be made to resonate at amazingly constant frequencies ranging from a few thousand to more than 100 million vibrations per second. The use of these oscillators multiplies the number of conversations that can be made simultaneously over a pair of telephone wires, and they have recently been installed to control observatory 'quartz clocks', which gain or lose less than one second in three years. Many thousands of tons of raw piezoelectric quartz have been exported from Brazil during the past few years for the manufacture of oscillator-plates.

Radioactivity is the property, possessed by certain elements of high atomic weight, of emitting radiations or emanations by the spontaneous disintegration of their atoms. Uranium, thorium, and actinium are strongly radioactive, whilst potassium, rubidium, and samarium are feebly so. In general, the radiations sent out by these substances are of three types, known as alpha-, beta-, and gamma-rays, the alpha-rays consisting of positively charged atoms of helium, the beta- of negatively charged electrons, and the gamma- of highly penetrating rays analogous to those of visible light but of very much shorter wave-length. The expulsion of these particles from uranium, thorium, and actinium at a fixed and unalterable rate eventually results in the production of the gas helium, and as a final stable end-product, the inert metal lead. In the case of uranium one of the intermediate products of decay is the important element radium, which itself emits the heavy inert gas radon (radium emanation).

Helium tends to escape from the place of its formation, but the lead accumulates at a constant and known rate within the parental radioactive minerals, which can thus be used as 'clocks' for measuring geological time.[1] When present in very ancient rocks the mineral uraninite (pitchblende) UO_2 may contain as much as 15 per cent of lead, whereas in comparatively recent igneous rocks very little lead has accumulated at the expense of the disintegrating uraninite. If the radioactive mineral contains thorium, its lead-generating power, which is 0·36 times that of uranium, must also be taken into account in making age determinations. Thus the amount of *derived* lead within a radioactive mineral which has crystallized in an igneous rock or mineral vein as an original constituent is directly proportional to the age of the rock or vein, and by making a chemical analysis of the radioactive mineral its age in millions of years can be determined. For approximate age calculations the so-called lead-ratio formula is:

$$\text{Age} = \frac{\text{Lead}}{\text{Uranium} + 0{\cdot}36\ \text{Thorium}} \times 7{,}600 \text{ million years.}$$

According to the present method of measuring geological time, based on the lead-ratios of radioactive minerals, the age of the oldest known rocks is at least 2,000 million years. Incidentally, the calculated ages of the now famous pitchblende deposits of the Great Bear Lake in Canada, and of the Belgian Congo, are respectively about 1,300 million and 600 million years.

The importance of *hardness,* one of the fundamental characters of minerals, was realized by our prehistoric

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[1] The atomic weights of 'radiogenic' lead are 206, 207, and 208 according to whether the metal is derived respectively from uranium 238, uranium 235, or thorium, whereas the 'common' lead found in metalliferous veins contains in addition the lead isotope 204. In the case of the mineral uraninite (pitchblende) reliable age determinations of the host rocks are based on the lead 206/uranium 238 ratio alone.

ancestors who sought eagerly for the hard mineral flint in order to fabricate sharp tools and weapons. As applied to minerals hardness is measured by the resistance offered by a smooth surface to abrasion or scratching. The determination of hardness or 'scratchability' is readily made by observing the effect when one mineral is scratched by another, or by a finger-nail, copper coin, or knife. For expressing the degree of hardness it has long been customary to use an arbitrary scale devised by Mohs, in which the following series of ten common minerals are arranged in relative order of increasing hardness:

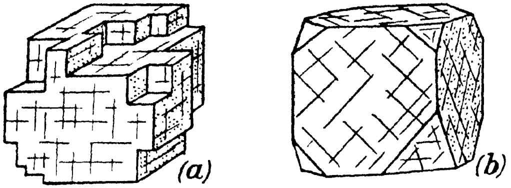
1 Talc; 2 Gypsum; 3 Calcite; 4 Fluorspar; 5 Apatite; 6 Felspar; 7 Quartz; 8 Topaz; 9 Corundum; 10 Diamond.

A mineral which scratches gypsum, for example, and is itself scratched by calcite, is said to have a hardness of 2½. In applying the test it is necessary to choose a fresh surface of the specimen, for earthy, granular, or splintery mineral aggregates may be crushed or crumbled without actually being scratched. For convenience, the determination of approximate hardness is greatly simplified by using a finger-nail (hardness 2½), a copper coin (3), knife-blade (5½), window glass (5½), or a steel file (6½). Most minerals are softer than a file, and with a little practice their hardness can be estimated by the ease with which they can be scratched by this instrument or by the point of a pocket knife. Certain gem-stones and their imitations may often be distinguished by this simple test.

It should be emphasized that the numbers in Mohs' scale merely indicate an order of relative hardness, and have no quantitative significance whatever. We must not, for instance, suppose that diamond is twice as hard as apatite or ten times as hard as talc, or that the interval of hardness between successive minerals in the scale is uniform. Indeed, a much greater gap exists between corundum and topaz than between topaz and quartz, and on an absolute scale the difference between corundum and diamond exceeds that between the first and the ninth mineral in Mohs' scale. Delicate tests show that the hardness of most minerals varies slightly according to the direction in which they are scratched, but with the remarkable exception of kyanite, with a hardness of about 4 parallel to its length and of 7 normal thereto, the variation is practically insignificant.

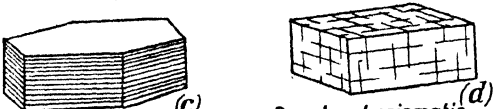
In ionic minerals hardness can be correlated with the strength of binding between the ions, increasing hardness being generally associated with closer packing of the ions in the crystal lattice, with reduction in the size of the ions, and with increase in ionic charge or valence of the constituent ions.

The way in which a mineral breaks is closely related to the internal arrangement of its atoms. Many minerals split easily in certain regular directions so as to yield smooth plane surfaces called *cleavage planes*. The 'cleavages' are always parallel to an actual or possible crystal face and usually occur along one of the principal planes in the lattice in which the atoms are closely packed together. Normal to these planes the atomic spacing is wider and the electrostatic binding forces are relatively weak, cohesion thus being at a minimum across the cleavages. It is important to remember that a mineral which possesses cleavage may be split up indefinitely parallel to its direction of cleavage. For example, mica has one perfect cleavage (Fig. 35, *c*) parallel to which the mineral may be split into successively thinner sheets down to less than a thousandth of an inch in thickness. The micas have structures based on continuous sheets of SiO_4-tetrahedra (see page 64) which are linked loosely through intervening potassium ions, cleavage resulting from rupture of the feeble oxygen–potassium bonds which hold the strong sheets together. In the pyroxenes and amphiboles (Fig. 28, page 63) cleavage takes place parallel to the length of the strongly bound chains of silicon-oxygen tetrahedra and never crosses them. Their cleavages are alined parallel to the vertical prism faces and in the two minerals they intersect respectively at approximately 90° and 120°.



Cubic cleavage - Galena

Octahedral cleavage - Fluor



Basal cleavage - Mica

Basal and prismatic cleavage - Barytes

Fig. 35. Cleavage in minerals.

Cleavage is described according to the ease with which it is obtained and the smoothness of the surfaces produced, and also according to its crystallographic direction.

Thus crystals of rock salt and galena (Fig. 35, *a*) are said to have perfect cubic cleavage because they can be readily split parallel to the faces of the cube so as to yield smooth, lustrous surfaces. Fluorspar, which commonly crystallizes as simple cubes, has perfect octahedral cleavage, for it splits perfectly along planes truncating the corners of the cube, and if the splitting is executed regularly an octahedron is produced (Fig. 35, *b*). A piece of calcite, no matter of what shape, breaks readily into rhombohedral cleavage-fragments on being crushed. Barytes, crystallizing in the orthorhombic system, has two sets of perfect cleavage, viz. a single basal cleavage and also two cleavage directions parallel to the vertical prismatic faces (Fig. 35, *d*). This example illustrates the universal rule that the directions of cleavage in a mineral are symmetrically repeated in accordance with the symmetry of the crystal. In many minerals the cleavage can only be described as good or fair, whilst in others, such as quartz, there is no tendency to split along regular smooth planes. The surfaces of fracture may be uneven, splintery, earthy as in chalk, or conchoidal with curved concavities as in broken flint (Fig. 36). It is clear, therefore, that the way in which a mineral cleaves or breaks serves as a valuable diagnostic feature.

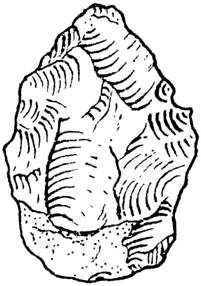


Fig. 36. Palaeolithic flint implement, showing conchoidal fracture.

Another important aid in the identification of a mineral is the determination of its *specific gravity* or density. The specific gravity of a mineral is clearly dependent upon the atomic weight of its constituent atoms or ions and upon the closeness with which they are packed together in the crystal structure. Thus, lead minerals are always heavy because that metal has such a high atomic weight; and although graphite and diamond both consist of carbon the latter mineral is much the heavier because its atoms are more tightly packed. If the specific gravity of a mineral is known and the dimensions of its unit cell have been ascertained by X-ray analysis, it is then possible to calculate the atomic contents of the cell. Conversely, if the composition and unit cell volume of a mineral have been determined, its density can be calculated. An intimate correlation thus exists between the specific gravity, chemical composition, and crystallography of any given mineral.

The extremes of specific gravity in minerals are represented by 1·1 in the fossil resin, amber, and 23 in iridium. With practice it is possible simply by handling a specimen to estimate its density approximately, and so to distinguish between minerals of somewhat similar appearance. For non-metallic minerals the average density lies between 2·60 and 2·75, because the most common and abundant species, quartz, felspar, and calcite fall within this limited range. Barytes, sometimes known as 'heavy spar', $BaSO_4$, and the lead carbonate, cerussite, with specific gravities of 4·5 and 6·5 respectively, are unusually heavy for minerals with a non-metallic lustre. Among metallic minerals the average density is usually considered to be about 5·0, corresponding to that of the commonest sulphide, iron pyrites, FeS_2.

Of the various types of balance used for determining specific gravity the most recent one designed for work on minerals is a delicate microbalance, capable of determining accurately the density of fragments weighing less than 25 mg. (under one-thousandth of an ounce). An indirect method of measuring specific gravity, which is both quick and convenient, is that employing heavy liquids, such as bromoform (sp. gr. 2·89), methylene iodide (3·33), and Clerici solution (about 4·2), whose densities can be lowered at will by appropriate dilution. Most metallic minerals sink when immersed in these liquids, but a mixture of non-metallic minerals can usually be separated into its component species by suitably varying the specific gravity of the liquids. Minerals which remain in suspension, neither rising nor sinking, have the same density as that of the enclosing liquid, which can be quickly determined by means of a special balance.

CHAPTER VII

MINERALS AND ROCKS

We have already observed that rocks may be divided into three great groups—igneous, sedimentary, and metamorphic. The crust of the earth is dominantly composed of *igneous rocks* that owe their origin mainly to the solidification of molten rock material known as magma. This fluid magma, charged with gases, is generated under intense heat within or below the crust at depths ranging from about ten miles to several hundred miles. Since the magma normally has a lower specific gravity than solid rock, and is subjected to enormous pressure, it is forced upwards and so penetrates and invades the crustal rocks. The magma may eventually reach the surface of the earth and pour out from volcanoes or open fissures as flows of lava, or be blown into the air in the form of 'bombs', fine ash, and explosive clouds of gas.

Lavas erupted at the surface are called *extrusive* or *volcanic* rocks, after Vulcan, the god of fire. On the other hand, those rocks which have solidified within the crust from magma that has failed to reach the surface are styled *intrusive* rocks. The major deep-seated intrusions are often designated as *plutonic*, after Pluto, the god of the infernal regions, and the minor, shallower intrusions which commonly form steep wall-like masses (dykes) and flat-lying sheets (sills) are distinguished as *hypabyssal*.[1]

The grain or texture of an igneous rock varies according to the cooling-history of the parent magma, and

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[1] See H.U.L. volume *Geology*, by Professor H. H. Read.

especially upon its degree of fluidity and rate of solidification. During very slow cooling the atoms are able to arrange themselves regularly into the space-lattices of the growing crystals so that the resulting rock is entirely crystalline and coarse-grained. Such a texture is characteristic of the plutonic rocks, including granite, which have consolidated slowly beneath a cover perhaps many miles thick. The component crystals of these rocks are mostly so large (more than 2 mm. across) that they can be distinguished by the unaided eye. More rapid cooling of the magma results in the development of a fine-grained rock consisting of small crystals, whilst sudden chilling prevents the atoms from disposing themselves symmetrically and therefore produces a glass. Extrusive rocks, such as basalt, that have cooled relatively quickly from lava poured out on the surface, may be wholly glassy or vitreous, though usually they consist of minute crystals embedded in a glassy base. In some cases comparatively large crystals may have grown in the magma before its eruption as lava, the resulting texture of the solid rock being known as *porphyritic* owing to the presence of big crystals set in a fine-grained groundmass. Moreover, the expansion of gases in the magma consequent upon release of pressure during its outpouring frequently gives rise to gas-blown cavities or vesicles, the rock texture being then called *vesicular*. These vesicles may remain empty, or they may subsequently become lined with crystals, often beautifully formed; when completely filled the almond-shaped 'bubbles' are known as amygdales, and the rock texture as amygdaloidal.

We noted on page 20 that the average content of silica (SiO_2) in igneous rocks is approximately 59 per cent; the amount actually varies from over 80 to less than

40 per cent. Magmas rich in silica are said to be *acid*, whereas those with much less silica and correspondingly more bases (alumina, iron oxides, lime, magnesia, soda, and potash) are referred to as *basic*. The basic magmas are more fluid than acid ones and consequently they offer greater freedom for atomic diffusion during the period of cooling, with the result that basic lavas and intrusive rocks tend to be coarser-grained than their acid counterparts. Even in acid magmas, however, the separation of early formed minerals may leave a residual liquid rich in volatile fluxes (gases and vapours) whose presence promotes the development of large crystals. Indeed, during this late *pegmatite* phase enormous crystals—in some cases many tons in weight—may be formed, such as those of felspar, mica, beryl, and tourmaline in granite-pegmatites.

As the magma cools and consolidates, its constituents unite to build rock-forming minerals, the great majority of which are silicates. It is a remarkable fact that despite their diverse and complex chemical composition the dominant igneous rock-types consist essentially of only six mineral groups, namely felspars, quartz, micas, pyroxenes (especially augite), amphiboles (mostly hornblende), and olivine. In acid rocks the light coloured minerals, notably quartz and felspar, predominate and yield much paler rocks than those of basic types, these latter being characterized by an abundance of dark silicate minerals rich in iron oxides and magnesia (i.e. ferromagnesian), particularly olivine, pyroxenes, amphiboles, and dark mica. Granite, the most common acid rock, includes on an average about 31 per cent of quartz, 52 per cent felspars, and 12 per cent mica. Basalt, by far the most widespread basic igneous rock, normally contains approximately 46 per cent felspars, 37 per cent pyroxenes, nearly 8 per cent olivine, and no quartz (Fig. 37).

Igneous rocks are often classified according to two factors, (i) the kinds and proportions of their constituent minerals, these depending upon the chemical composition of the magma, and (ii) their mode of occurrence, which largely controls the kind of rock texture.

	Acid	Intermediate	Basic
EXTRUSIVE (Volcanic)	RHYOLITE	ANDESITE	BASALT
MINOR INTRUSIVE (Hypabyssal)	QUARTZ PORPHYRY	PORPHYRITE	DOLERITE
MAJOR INTRUSIVE (Plutonic)	GRANITE	DIORITE	GABBRO

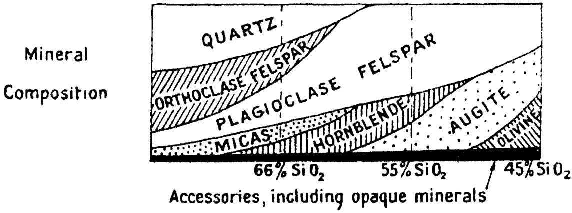

Fig. 37. Table of Principal Igneous Rocks.

A skeleton classification is outlined in Fig. 37, in which the igneous rocks are grouped arbitrarily into three columns in the order of their silica content, thus: Acid, with more than 66 per cent SiO_2, Intermediate, with between 66 and 55 per cent SiO_2, and Basic, with less than 55 per cent SiO_2. Each column contains a typical coarse-grained plutonic member, together with a hypabyssal rock (mainly fine-grained), and a glassy or very fine-grained extrusive or volcanic representative. The continuous variation in mineral composition from acid to basic rocks is shown graphically, the subordinate accessory constituents (including opaque minerals) being indicated in black at the base of the diagram. From this illustration it is clear that the igneous rocks can be classified mineralogically according to the presence or absence of quartz, the nature of their felspars, and the kinds of ferromagnesian minerals they contain.

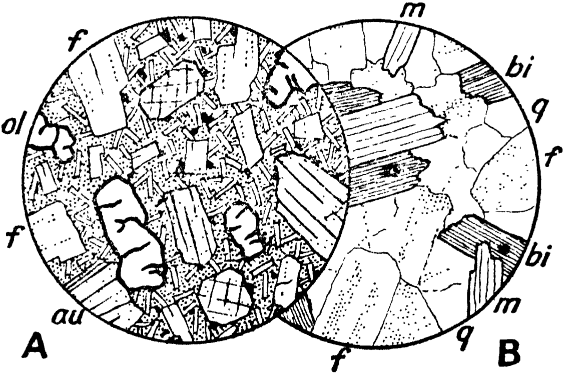

Fig. 38. Igneous Rocks in Thin Section. A. Olivine Basalt; large crystals of olivine (*ol*), augite (*au*), and felspar (*f*), in a ground mass of small felspar laths, minute granules of magnetite, and basic glass. B. Granite; interlocking crystals of quartz (*q*), felspar (*f*), and two micas, muscovite (*m*) and biotite (*bi*), partly in parallel intergrowth. (Magnification: × 10.)

Beyond the extreme basic end of the table there is a small assemblage of rocks classed as *ultrabasic*, which contain little or no felspar and are composed almost entirely of ferromagnesian minerals, especially olivines and iron oxides. A large proportion of intrusive rocks consists of granite, though its lava equivalent, rhyolite, is not an abundant type. In contrast, the most widespread of all lavas is basalt, but its coarse-grained plutonic equivalent, gabbro, is not especially common.

The appearance of two of the commonest igneous rocks as seen under the microscope is illustrated in Fig. 38.

Measurements of the temperatures of recently erupted lavas indicate that they may range from 600° C. to about 1,200° C., the basic lavas being the hottest. These temperatures are considerably higher than those at which the corresponding deep-seated magmas consolidate to form plutonic rocks, where crystallization is retarded by the retention of gaseous fluxes in the cooling magmas.

During the solidification of magmas there is a marked tendency for the principal silicate minerals to crystallize out in a definite order. Among the ferromagnesian silicates the earliest to form are those with the simplest atomic structures, based on separated SiO_4 tetrahedra—notably, the olivines. On further cooling this simple type of crystal architecture becomes unsuitable and is succeeded in turn by the single chain pattern characteristic of the pyroxenes, by the double chain structure of the amphiboles, and by the extended sheets of linked tetrahedra typical of the micas. With falling temperature there is thus an increasing complexity in the crystal structure of successive minerals, whose density and index of refraction diminishes progressively. Concurrently with the sequence of changes from olivine to mica, the plagioclase felspars change gradually from calcic to sodic types, to be followed by the crystallization of potash felspar and quartz as final major products of consolidation. The chief basic rocks, such as basalt, are consequently characterized by the dominance of lime felspar, olivine and pyroxene, whilst the acid rocks, including granite, consist essentially of potash felspar, quartz, and mica.

Those minerals that begin to crystallize early during the solidification of magma may actually complete their growth without interference and thus develop perfect crystal form. On the other hand, the latest minerals are usually quite irregular in outline, for they must perforce occupy the interstitial areas remaining between the minerals of earlier growth.

The *sedimentary rocks* are mostly composed of the material of pre-existing rocks which have been broken down by exposure to weathering at the earth's surface. These products of disintegration are usually transported from their place of origin, either as solid particles or in solution, and after being distributed by wind and water they are ultimately laid down in layers as stratified deposits. Most of them accumulate in the sea in a loose, unconsolidated form and are later subjected to compaction, cementation, and induration.

Although the sediments probably cover more than three-quarters of the entire land surface, they constitute only about 5 per cent of the crustal rocks, for they exist merely as a discontinuous veneer averaging perhaps half a mile in thickness. They can be classified conveniently on the basis of origin into three groups: (i) *Mechanically formed* sediments, consisting of worn fragments of older rocks which have been carried into their present position by wind, water, or ice. They include gravels, sands, sandstones, clays, and shales; (ii) *Chemically formed* sediments, formed of material dissolved from pre-existing rocks and subsequently precipitated from solution, e.g. many limestones, and saline deposits formed by evaporation; (iii) *Organically formed* sediments resulting mainly from the accumulation of vast quantities of organic remains, e.g. shelly limestones, phosphate deposits, and coals.

Shales and clays comprise about 80 per cent of all sedimentary rocks, sandstones 15 per cent, and limestones about 5 per cent. All the other kinds of sediments constitute only a very small proportion of the grand total. The relative abundance of shales is due to the fact that, with the exception of quartz, the principal minerals in igneous rocks, namely felspars and ferromagnesian silicates, break down to yield the so-called clay minerals. These are minute flaky hydrous aluminium silicates, such as kaolinite, characterized by a sheet-lattice structure. They are accompanied by innumerable tiny scales of mica and chlorite, together with finely divided quartz, calcite, colloidal silica, iron oxides, &c.

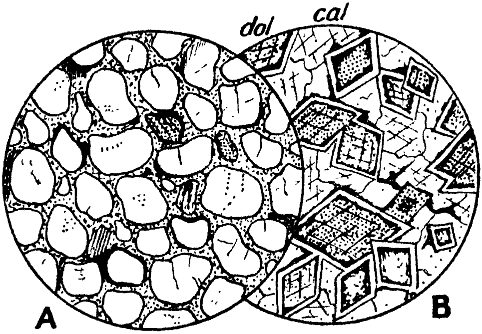

Fig. 39. Sedimentary Rocks in Thin Section. A. Sandstone; rounded quartz grains with cement of silt. B. Dolomitic Limestone; rhombs of dolomite (*dol*) in a matrix of calcite (*cal*). (Magnification: × 10.)

Sandstones consist dominantly of more or less rounded grains of quartz, a hard insoluble mineral not easily reduced by abrasion (Fig. 39, A). According to the cementing material between the quartz grains it is possible to distinguish several varieties, including calcareous sandstone with a cement of calcite, ferruginous sandstone cemented by red or brown iron oxides, siliceous sandstone with intergranular finely divided quartz, and argillaceous sandstone with a clayey bond. Limestones, whether of organic or chemical origin, are composed principally of calcium carbonate in the form of calcite or, occasionally, aragonite. Dolomite, the double carbonate of calcium and magnesium, is often an important constituent of calcareous rocks, the amount increasing during the passage from dolomitic limestone (Fig. 39 B) into pure dolomite.

Metamorphic rocks result from the transformation of preexisting rocks under the influence of heat, stress, and migrating fluids. Changed physical and chemical conditions may result in many minerals in the original igneous, sedimentary, or metamorphic rocks becoming unstable and consequently susceptible to replacement by new minerals more in harmony with the altered environment. The new species develop whilst the rocks remain essentially solid, and frequently textures are produced which are quite unlike those of the original rocks.

Thermal or contact metamorphism is developed by the baking action of a hot igneous mass on the surrounding rocks, and commonly results in recrystallization of some or all of the original rock constituents. In a sandstone the quartz grains are recrystallized into an interlocking mosaic of quartz crystals so as to form quartzite. Pure limestones are converted into marbles, and limestones containing impurities such as magnesia and silica are changed into marbles studded with various silicates, notably olivine, forsterite, lime garnet, pyroxenes, and amphiboles (Fig. 40, B). Clayey rocks may be metamorphosed into tough fine-grained rocks known as hornfels, which are often characterized by the presence of aluminium silicates such as andalusite and sillimanite, together with biotite, cordierite, and staurolite.

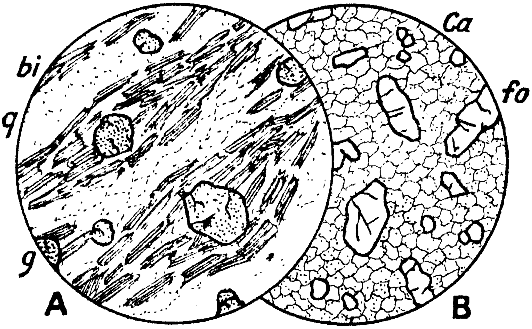

Fig. 40. Metamorphic Rocks in Thin Section. A. Garnet-Biotite Schist; principal constituents are garnet (*g*), biotite (*bi*), and quartz (*q*). B. Forsterite Marble; crystals of forsterite (*fo*) set in an even-grained matrix of calcite (*ca*). (Magnification : × 10.)

Stress, or dynamic, metamorphism promotes the growth of new minerals of platy or bladed habit arranged with their flat sides at right angles to the direction of maximum stress. The metamorphosed rocks thereby acquire a parallel structure or banding known as foliation or schistosity. Shales are transformed into slates in which the small flaky minerals, such as mica and chlorite, lie with their platy surfaces parallel to the slaty cleavage, and the tiny quartz grains become flattened and elongated in the same direction. With increased metamorphism slates pass into fissile mica schists. Basic igneous rocks containing pyroxenes may be converted by pressure into chlorite or hornblende schists, and olivine-rocks give rise to serpentine and talc schists, whereas granites and sandstones are commonly changed into banded gneisses. Among the accessory constituents often present in schists and gneisses are certain dense well-developed minerals such as pink garnet, cross-shaped staurolite, and bladed blue kyanite, whilst the soda plagioclase, albite, is usually the dominant felspar (Fig. 40, A).

CHAPTER VIII

ECONOMIC MINERAL DEPOSITS

MINERAL DEPOSITS are accumulations or concentrations of useful minerals, such as the fuels which include coal, lignite, and petroleum; the non-metalliferous minerals, barytes, fluorspar, gypsum, sulphur, and many others; and the metalliferous minerals which yield the world's supply of gold, platinum, copper, tin, tungsten, lead, zinc, and a host of other metals. Only passing reference is made in this chapter to the fuel deposits.

When we refer to deposits which are important chiefly for the *metals* extracted from the minerals, the term 'ore deposits' is generally used. Technically, an ore is an accumulation or concentration of minerals from which one or more metals can be profitably extracted. As the market value controls whether a mineral will pay for its extraction, what is ore one year may technically not be ore the following year ! But the term ore is often used loosely for almost any material that is obtained from a mine. Many orebodies yield, besides metalliferous minerals, others, such as fluorspar and barytes, as useful by-products.

Most minerals have been formed by precipitation from liquid solutions or gaseous emanations, but chiefly from liquid solutions. The two principal factors which effected precipitation were the temperature and pressure conditions prevailing at the time the minerals were formed. In general, and within limits, decrease of temperature and pressure promote the precipitation of minerals from solution, but decrease of pressure is thought to be less effective than fall of temperature in causing precipitation from aqueous mineralizing solutions.

THE ORIGIN OF MINERAL DEPOSITS

There are several natural processes by which useful minerals have been accumulated, or become concentrated, to form deposits of economic importance. Some of the chief of these processes will now be described briefly.

Rocks of igneous origin are formed by the consolidation of molten material called rock magma, or simply, magma. During consolidation the first minerals to crystallize are usually the heavy ones, and this may result in the concentration of those minerals by gravity-settling during solidification of the magma. It does not follow that these heavy minerals will always occur at the base of the consolidated rock. Crustal movements may force the minerals to occupy fissures in the surrounding rocks, though almost all deposits formed by direct segregation from the magma are found either in or near the igneous rocks with which they are genetically related.

The famous Swedish magnetite deposits of Kiruna and Gellivare, which supplied Germany before and during the second world war with the millions of tons of iron ore shipped annually from the Norwegian port of Narvik, were formed by direct crystallization from a magma which also yielded syenite (consisting largely off felspar and hornblende). Almost all the world's deposits of chromite were formed by a similar process, but from a much more basic magma which consolidated as an ultra-basic igneous rock (Fig. 41).

Many authorities believe that diamonds were also formed by direct crystallization from molten rock rich in carbon, though the source of the carbon is controversial. Some maintain that it was derived from carbonaceous shales that became incorporated in the magma, and others that the carbon was an original constituent of the magma. In the South African diamond field, the diamonds are disseminated in volcanic pipes which are filled with a serpentinized rock derived from the olivine-rich rock peridotite, and usually called 'kimberlite' from its occurrence near Kimberley. The Kimberley pipe has been worked to a depth of nearly 4,000 feet, where it is about 500 feet in diameter (see Fig. 42). Near the surface the kimberlite is decomposed into 'yellow ground' but at greater depth, where the rock is less decomposed, it is known as 'blue ground'.

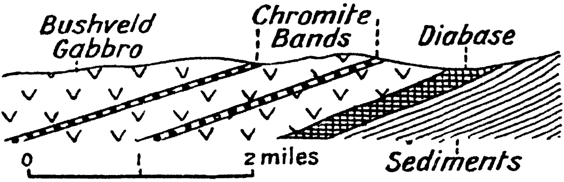

Fig. 41. Stratified chromite bands in the Bushveld gabbro, Transvaal.

Sapphires and rubies may crystallize from magmas rich in aluminium, but those at the famous Burma ruby mine were formed mainly in a limestone which had been greatly altered by contact with an acid igneous rock.

If sulphides are present in large quantities in the magma, then separation by unmixing takes place during cooling. It was formerly believed that the sulphides are among the first minerals to separate out from the molten rock, but there is now considerable doubt concerning the stage of cooling at which the separation takes place. Indeed, some of the world's most important sulphide deposits which were once considered to have originated by direct separation from the magma, are now believed by many authorities to have been deposited by hot aqueous solutions which emanated from an igneous source. Controversies have raged, for example, about the origin of the famous sulphide-nickel deposits of Sudbury, Ontario, which produce about 80 per cent of the world's nickel; about the Rio Tinto cupriferous pyritic

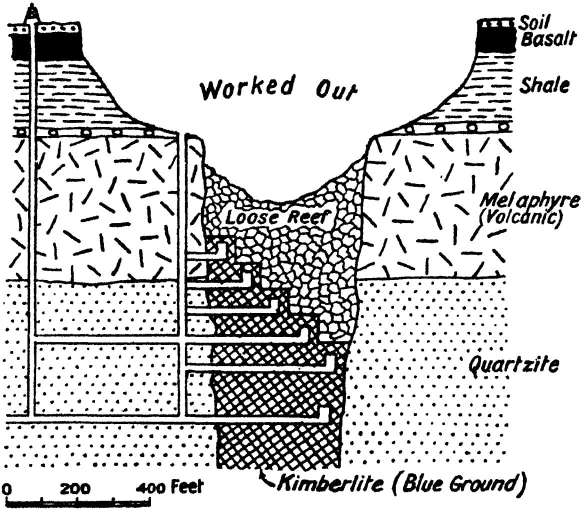

Fig. 42. Diagrammatic cross-section of Kimberley diamond pipe, South Africa.

deposits in Spain, the largest known of their kind; and concerning many other important deposits of sulphide minerals. We shall not discuss the merits of the different theories, but have mentioned them so that the reader may realize that the origin of certain types of deposits is difficult to determine.

We have referred to the heavy minerals which sink in the magma, but have not considered the lighter minerals which crystallize without separation by gravity sinking.

The upper parts of some magmas are high in silica, and during consolidation minerals like quartz, the alkali felspars, micas, and other silicates form. Some magmas, particularly those of this acid type, are rich in volatiles. During the solidification of the main part of such magma to form a rock like granite, these volatiles become concentrated in the residual and more acid portion of the molten material, which is thus able to remain fluid at lower temperatures than it would without the fluxing effect of the volatiles. When, therefore, fissures are formed in the granite during or after its solidification, and cracks develop in the adjacent rocks, channels are provided into which the residual acid magma with its volatiles can be forced by crustal pressure. The veins of quartz, pegmatite, aplite, and quartz porphyry (the two latter are often termed 'elvans') which are so common in the tin-mining areas of Cornwall and Devon were probably formed in this way.

Water vapour is present in magmas, and some acid magmas contain fluorine, boron, sulphur, and other non-metals which act as carriers of such metals as tin, tungsten, and copper. When these volatile mineralizing agents ascend and reach a zone where the temperature and pressure conditions are suitable, they deposit the tin as cassiterite, SnO_2; the tungsten as wolfram, $FeMnWO_4$; and the copper as chalcopyrite, $CuFeS_2$. That is one and perhaps the chief way in which the tin and tungsten lodes in Cornwall and Devon and other tinfields were formed. Under somewhat lower temperature conditions such deposits were probably also formed by ascending aqueous mineralizing solutions.

Contact-metamorphic (*Pyrometasomatic*) *Deposits.* Sedimentary rocks which are in contact with igneous intrusions may be considerably changed by the heat and pressure developed by the intrusion. New minerals, like garnets, amphiboles, pyroxenes, and other silicates, may be formed in the invaded rocks, and metallic and other useful minerals may be developed at the contacts, chiefly of limestone and calcareous shales with granite, granodiorite, and quartz monzonites, but rarely at the contacts of basic igneous rocks. The useful deposits lie in a belt or zone near the contact, are generally irregular in shape, and can be distinguished from lode and other deposits by their independence of fissuring and by their mineral assemblage, which is almost invariably an inter-

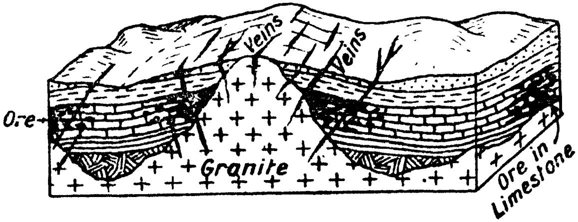

Fig. 43. Idealized diagram showing location of mineral veins, and of orebodies (in black) formed by replacement of limestone adjacent to a granite cupola.

growth of silicates with the oxides and sulphides of metals such as iron, copper, zinc, and, less frequently, gold, silver, and lead. Such deposits are the result of metasomatism; that is, they were formed by replacement of the invaded rock largely by material which emanated from the adjacent intrusive mass. Their temperature of formation was high and hence they are frequently known as pyrometasomatic deposits.

Hydrothermal Solutions. The water emanating from an igneous source is often termed 'juvenile water', whereas that of atmospheric origin is known as 'meteoric water'. Juvenile water usually carries silica in solution and may also contain metals and non-metals. During its passage upwards through fissures in the rocks it reaches zones where, as the result of falling temperature, it is unable to carry its burden with the result that precipitation takes place and deposits of economic importance may thus be formed. Such deposits may be confined to the channels traversed by the mineralizing solutions, or to the conduits enlarged during this passage, to form mineral veins. If the veins contain metalliferous minerals they are termed 'lodes' in this country, whereas in the U.S.A., that term is applied not to single metalliferous veins but only to those of a composite nature.

In the great majority of cases the juvenile water during its journey through fissures dissolves, or partly dissolves, much of the adjacent rock and may replace it with a mineral deposit. Some rocks, notably limestone, are more easily replaced than others, but most rocks are susceptible to this change to some degree. Consequently, this process of mineralization by replacement is a major factor in the formation of a very large number of important mineral deposits.

So far, we have considered aqueous mineralizing solutions irrespective of the temperatures existing during the deposition of their burden. So crucial, however, are these temperature conditions in determining the types of deposits formed, that they require further attention.

It has been found convenient to regard deposits of hydrothermal origin as having been formed under three main states of temperature conditions. Those deposited when the temperature was from 300° to 500° C. are the high temperature, or *hypothermal* deposits; those at temperatures from 200° to 300°, the intermediate or *mesothermal* deposits; and those at 50° to about 200°, the low temperature, or *epithermal* deposits.

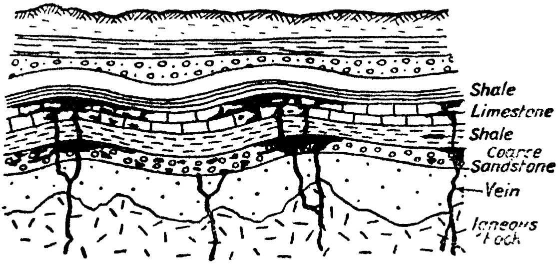

Fig. 44. Diagram illustrating formation of ore (shown in black) in sedimentary rocks due to impregnation and replacement by ore-bearing solutions of igneous origin.

The criteria by which hydrothermal deposits are assigned to one or other of the three types are numerous, but only a few of them need be mentioned here.

Certain minerals including magnetite, specular hematite, pyrrhotite, cassiterite, wolframite, tourmaline, and topaz are generally formed only at high temperature.

Their presence in a deposit is therefore an indication that high temperature conditions probably obtained during its formation. Cinnabar, the tellurides of gold, and certain other minerals cannot be formed in quantity except in a comparatively low temperature environment, and their occurrence in a deposit usually points to an epithermal origin. It should be stressed, however, that some minerals, such as pyrite and quartz, can be deposited at both high and low temperatures, so that normally the *suite* of minerals, rather than one or two species, is taken into account when interpreting the temperatures of formation.

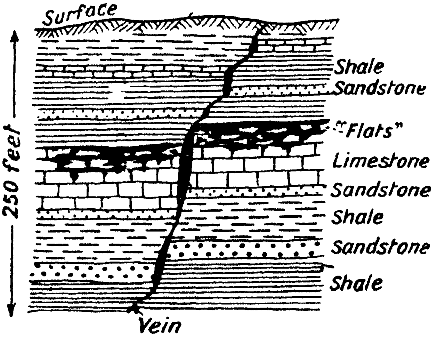

Fig. 45. Lead-zinc vein in fault cutting sedimentary strata, with associated replacement 'flats' in limestone.

Although quartz can form at high and low temperatures it is, nevertheless, one of the most useful minerals in geological thermometry. Below a temperature of 575° C. it changes from *beta* quartz to *alpha* quartz with a different recognizable symmetry. Gold may also originate under different temperature conditions, but it is an interesting fact that, in general, the gold in high temperature deposits generally contains less silver than that formed epithermally.

The nature of the deposit is another important factor in relation to the temperature obtaining during its formation. Veins of high temperature origin have different characteristics from those formed under low temperature. The latter are frequently distinguished by the presence of cavities, banded arrangement of the minerals, and irregular walls, and their influence on the adjacent rocks differs from that of the high temperature veins.

The chief hydrothermal deposits of economic importance formed under high temperature conditions are the tin and tungsten lodes, such as those of Cornwall; the gold-bearing veins and replacements which persist to great depths, like those of the Kolar goldfield in India, St. John del Rey in Brazil, the Porcupine and Kirkland Lake goldfields of Ontario, Canada; and some of the largest known lead-zinc deposits, including those now being worked at Sullivan mine in British Columbia; at Broken Hill, New South Wales; and at the Bawdwin mines in Burma.

Many lead and zinc deposits were not, however, formed at high but at intermediate temperatures. Among other deposits formed mesothermally are the gold-quartz veins of California, and of Victoria in Australia; the silver-tin veins of Bolivia; and some very important copper deposits, the most prominent being the famous ore-bodies worked at Butte, Montana. These latter produce annually over 120,000 tons of copper, about 64,000 tons of zinc, and some 10 million ounces of silver. The famous pyritic deposits of Rio Tinto and of other parts of Spain are also generally regarded as having been formed under these conditions.

Unlike the hypothermal and mesothermal gold deposits, those formed under relatively low temperature conditions do not persist to great depth. This is well illustrated by the epithermal deposits in which the gold is generally present as a telluride, frequently high in silver. Such gold occurrences may be spectacularly rich for the first few hundred feet but at greater depth often prove unworkable. For example, the gold telluride veins of Cripple Creek, Colorado, produced in the year 1900 about £3½ million of gold; in 1916 it was £2½ million; in 1925 less than £1 million, and in 1931 well below half a million sterling. Production on this goldfield, as at the famous Comstock Lode in Nevada which is also an epithermal deposit, has now virtually ceased.

The world's supply of mercury comes from cinnabar deposits, and that of antimony from stibnite deposits. These two are also types of low temperature hydrothermal deposits.

Some of the mineralizing solutions ascending from magmatic sources reach the surface as hot springs, and as tepid springs when mixed with surface water. Such solutions are very common in regions of recent or fairly recent volcanic activity. It should be made clear, however, that hot springs may also result from the deep penetration of circulating waters, but usually these do not carry metalliferous minerals, except as traces. At Steamboat Springs, Nevada, hot springs at a temperature of 75° to 85° C. emerge along a fissure about a mile in length. Steam, hydrogen sulphide, sulphur, and small amounts of the sulphides of arsenic, antimony, lead, copper, and mercury are present with some gold and silver. Similar hot springs in Colorado are now depositing gold, silver, fluorspar, and barytes. No hot-spring deposits have however been proved to be of economic importance, but they have been referred to here to complete the natural history of the mineralizing solutions in their ascent from their magmatic source.

Zonal Arrangement of Minerals. The study of ore deposits within a mineralized area about the centre of an igneous intrusion, has shown that the minerals formed at high temperature have a tendency to lie closest to the magmatic source, the lower temperature minerals in more distant zones, and those formed at intermediate temperature occur between these two zones. The ideal sequence, beginning with the highest temperature zone, would be the minerals of (i) tin and tungsten; (ii) gold; (iii) copper; (iv) zinc; (v) zinc and lead; (vi) lead; (vii) gold and silver; (viii) antimony; (ix) mercury. The complete sequence is not known to occur anywhere, but in certain mineralized districts parts of this sequence are clearly illustrated. For example, Dolcoath mine in Cornwall began as a copper mine and at deeper levels passed through the copper zone and became a tin mine with no copper production. At Butte, Montana, a pronounced zonal arrangement of copper, zinc, and lead, in that order from the centre of the parent intrusion, has been established, and in other parts of the world evidence has been accumulated strongly supporting this theory of the zonal arrangement of minerals laterally and in depth.

We have now considered the chief of the mineral deposits which were formed by direct separation from the magma; those formed as veins or lodes which derived their material mainly from magma; and the concentrations which owe their origin to hydrothermal solutions which emanated from igneous sources and formed valuable deposits under high, intermediate, and relatively low temperature conditions. Even the latter were in most cases formed at temperatures above the boiling point of water. There are however accumulations of useful minerals of the greatest importance which were deposited at temperatures well below the boiling point of water and even at ordinary surface temperatures.

We shall first consider the deposits formed by transportation and concentration by surface waters.

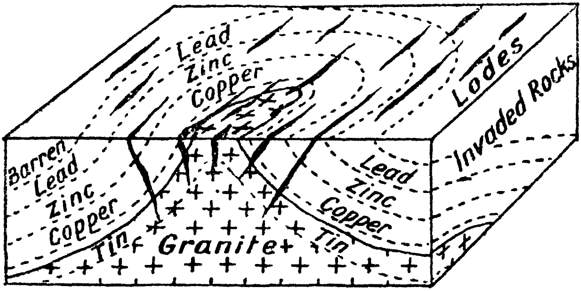

Fig. 46. Diagram illustrating zonal arrangement of metals (tin, copper, zinc, and lead) in lodes around a granite intrusion. (Modified after Emmons.)

Deposits formed by Transportation and Concentration by Surface Waters. During the weathering of rocks, some of the minerals of which they are composed may undergo changes to form new minerals, and others may retain their original chemical composition. When erosion takes place, the rock material is carried down the slopes into channels where running water effects a mechanical separation of the minerals. The heaviest particles tend to become concentrated in the upper reaches of the streams, the lighter particles further from the source, and the fine particles of clayey material are carried considerable distances, ultimately to be laid down in lakes and seas as sedimentary beds. The material in colloidal form is often carried out to sea where it is coagulated by the electrolytes in sea-water.

Quartz is a comparatively light and very stable mineral, and as it forms one of the chief constituents of many types of rocks, accumulations of beds of quartz are very plentiful as sand, sandstone, and quartzites. Some beds of sand are composed of almost pure quartz and are used extensively as ingredients in the manufacture of glass and pottery. When such sands have been compacted by pressure and natural cementation into highly siliceous sandstones and quartzites, they can often be employed as millstones and, if of suitable grain-size, as whetstones and grindstones.

The fine material derived from the decay of rocks is deposited in river-beds, lakes, and seas as sedimentary clay. Most of the clay comes from the alteration of the felspathic minerals in the rocks. If such a clay is not discoloured by hydroxides of iron and other impurities, and remains white or almost white, it may form valuable deposits of kaolin or china-clay. Such deposits have accumulated in Georgia and South Carolina in the U.S.A. and are the chief sources of the kaolin used in that country for the manufacture of paper, pottery, and as a filler for cotton and rubber. The kaolin deposits of Cornwall and Devon however are not sedimentary deposits; their origin is described on page 125.

During the transportation of the clay in running water and its deposition in beds, it may become contaminated by other substances which endow it with properties unlike those of kaolin. The ball-clays worked in the north and south of Devon, and in the neighbourhood of Wareham in Dorsetshire, contain carbonaceous and other materials which give them high plasticity and relatively low fusibility, properties which make these clays suitable as one of the ingredients in the manufacture of certain types of pottery.

Clays like fuller's earth and bentonite have high absorbent properties which enable them to be used extensively for deodorizing, decolorizing, and clarifying fats and oils, including the refining of petroleum. The origin of fuller's earth is somewhat obscure, but bentonite is certainly often due to the decomposition of volcanic ash in sea-water.

Placer and Eluvial Deposits. Heavy minerals are less abundant in rocks than those of low specific gravity, and while they are not more resistant to decomposition than certain lighter minerals like quartz and muscovite mica, some of them have far greater stability than the felspars and other light minerals

When rocks containing such heavy and stable minerals as gold, platinum, cassiterite, magnetite, monazite, diamonds, and other precious stones are weathered and eroded, these minerals become concentrated in the lower parts of sands and gravel beds to form valuable *placer*, or alluvial, deposits. What has happened is that nature has forestalled, in a far more leisurely manner, what the mining engineer has to do daily—the breaking up of mineralized rock and the concentration of the useful minerals. By natural processes, the rocks are broken and comminuted by expansion and contraction resulting from heat and cold; by plant growth; by the attrition of rock fragments in running water; by the grinding action of ice; and by chemical decomposition and hydration. The placers of economic importance have accumulated in water-courses, on the banks of streams and rivers, in recent and ancient alluvial terraces, and along the shores where ocean currents have sorted the material by a process similar to that employed on tables and jigs in ore-dressing. Thus it is that the specific gravity of stable minerals plays the most important part in the formation of economic alluvial deposits. Diamond has a specific gravity of 3·52; monazite 5·0; cassiterite between 6 and 7; gold 15·6; and platinum as found in nature from 14 to 19. Of the common light minerals, quartz has a density of 2·65; felspar 2·55 to 2·75; and the ferro-magnesian silicates less than 3·5.

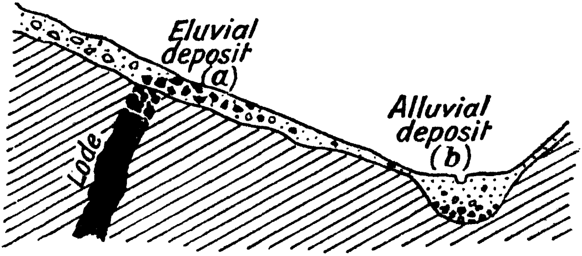

Fig. 47. Formation of (*a*) *eluvial* deposit on hill slope below lode outcrop, and (*b*) *alluvial* deposit (placer) by concentration of dense, resistant minerals (shown by heavy dots) along valley floor.

On hill and mountain slopes, especially those covered with vegetation in warm and moist tropical countries, a considerable thickness of weathered material may remain in situ, or may creep slowly down the slopes as angular fragments. Such accumulations of broken rock are known as *eluvial* deposits (Fig. 47), to distinguish them from alluvial deposits, in which the particles are rounded or sub-rounded and where sorting has been effected during transportation in running water. Even in eluvial deposits, especially those near the outcrops of gold veins, some degree of concentration has been effected; but even without natural concentration the useful minerals can be easily recovered from the loose ground.

Running water is however the most potent agency in the formation of the placer deposits which yield gold, tin, platinum, monazite, and precious stones. Most of the world's tin and monazite for example are obtained from sands and gravels in which the tinstone and monazite have been concentrated by sorting during transportation in water.

Most placer deposits lie on or near the surface but some, like the auriferous quartz conglomerate ('banket') of the Transvaal, S. Africa, which yields about a third of the world's gold, are in places buried under thousands of feet of newer rocks. It is highly controversial whether the gold in the banket of the Witwatersrand, Transvaal, was transported by surface waters and deposited at the same time as the enclosing conglomerate, or whether the metal was subsequently precipitated from ascending infiltrating mineralizing solutions of juvenile origin.

Deposits formed by Chemical Processes by Reactions between Solutions in Surface Waters. Plants and animals play a fundamental part in the concentration of certain elements. Living matter collects the needed elements; after death these elements are yielded to the materials of the environment in which the organisms lived, and the process may involve a sequence of concentrations. Thus blue-green algae concentrate phosphorus from sea-water; certain molluscs feed on the algae and they, in turn, are consumed by meat-eating molluscs which become the prey of small fishes which provide food for larger fishes. Birds eat the fishes and deposit excrement on desert islands to form valuable deposits of guano. The phosphates obtained as fertilizers from guano and rock phosphates have passed through half a dozen or so cycles of transformation before they are available for man's use.

Plants are continually accumulating carbon from the atmosphere. The plants decay on the surface to form, in places, beds of peat, or under a protective cover of water, clay, and sand to form beds of lignite and coal. Plants also take up potash, phosphorus, iron, and other elements. Seaweed for example contains about a dozen elements, including iodine. No metalliferous deposits of commercial importance have however been formed mainly by the agency of plants, although plant decay-products have played an important role in the precipitation from solutions of some metalliferous minerals.

In the formation of limestone, chalk, and dolomite, organisms have often been the chief agents either directly by life processes or indirectly by promoting precipitation of calcium carbonate by the ammonium carbonate generated by decaying organisms. Some limestones, although originally of organic origin, have been re-deposited from bicarbonate of calcium carried by fresh water into the sea and there precipitated as the result of a changed equilibrium in the solutions.

Most surface waters carry some iron in solution and under certain conditions the amount may be considerable, the maximum known being 9 per cent in some of the streams of Guiana, South America. Usually the iron is not carried far and, when the ferruginous waters flow into bogs and swamps, the iron is precipitated as limonite, the hydrated oxide of iron. Bog iron ore has been worked in many countries but not on a large scale and, except in one or two instances, is no longer of economic interest.

Oolitic marine iron ores are, on the other hand, of first-rate economic importance, for they are the main source of our domestic supplies of iron, yield most of the metal in Europe, and constitute important resources of iron in other parts of the world. Oolites are small, rounded, concretionary grains, resembling in form the roe of fish, whence the name was derived (Fig. 13, D, page 38). The oolites may be composed entirely of calcium carbonate as in oolitic limestone; of the iron carbonate, siderite, or of iron-rich chlorite (chamosite); of the hydroxide of iron, limonite; or of the oxide of iron, hematite. The iron-bearing oolites usually contain some colloidal silica and have been formed by colloidal processes. They are shallow-water deposits which have derived iron from nearby decomposing rocks, and their formation has been facilitated by wave action and currents, and by rapid fluctuations in the water level. It was formerly thought that the iron had been introduced into pre-existing oolitic limestone, but it is now generally believed that it was deposited contemporaneously with the oolites and that many complex changes took place during deposition.

The oolitic iron ores in this country stretch southwards from Yorkshire through Lincolnshire, Leicestershire, and Rutland into Northamptonshire, the chief mines being in Cleveland, Yorkshire, and in Northamptonshire. They are composed mainly of iron carbonate and although the ores are low grade, averaging less than 30 per cent iron, the large scale on which they are worked, chiefly opencast, make them by far the most important sources of iron in Great Britain.

The most productive oolitic iron deposits in the world are the famous 'minette' ores of Alsace-Lorraine which, in normal times, provided between 30 and 40 million tons of ore a year. They are composed mainly of limonite and, like those of this country, are of Jurassic age.

Deposits formed by Evaporation of Surface Waters. During the weathering of rocks, the easily soluble substances are carried by rivers into lakes, seas, and oceans. Under certain conditions the dissolved substances may become concentrated to form mineral deposits of immense commercial importance.

Crustal movements in parts of the world where folding, subsidence, and uplift have been in progress, may have given rise to closed basins or inland seas, like the Dead Sea in Palestine, the Great Salt Lake in Utah, and other basins in dry regions. In past geological times, notably during the arid climate of the Permian and Trias, the evaporation of sea-water, intermittently replenished with further supplies, resulted in the accumulation of great thicknesses of salt deposits. Those of Cheshire in this country, the famous Stassfurt deposits of Germany, and many others were formed in this way. At Stassfurt the beds of rock salt range from a few feet to over 1,000 feet in thickness, and are associated with potash salts, and with beds of gypsum and anhydrite which are also products of the evaporation of sea-water. The ideal succession during undisturbed evaporation of sea-water, commencing with the least soluble substance and thus the first to be precipitated, is briefly: calcium and magnesium carbonate; calcium sulphate; rock salt; and lastly the soluble salts of potash and magnesium. An almost complete succession of these substances occurs in the Stassfurt deposits.

Sodium nitrate is a very soluble salt and occurs in nature only under exceptionable conditions. The nitrogen it contains may be derived from the air by organisms and from rain-water during electric atmospheric discharges, or as some believe, from the leaching of nitride-bearing volcanic rocks under arid conditions. The only known important deposits of sodium nitrate ('Chile saltpetre') are in the Atacama and other deserts of northern Chile. These deposits in normal times yield also the world's chief supply of iodine. Some iodine is also obtained from seaweed in Japan, England, and other countries; and from brine in the U.S.A.

Borates, mainly as borax and kernite, are found in the neighbourhood of hot springs and lakes in volcanic regions. The borates are deposited as a thick encrustation by the evaporation of the water and as an efflorescence on the surface of desolate, arid plains such as those between the ranges of volcanic rocks in the deserts of California, Nevada, Bolivia, and Chile.

Residual Deposits. In moist tropical and sub-tropical regions of heavy vegetation, the weathering of rocks may extend to depths of 100 to 250 feet and more, and in soluble rocks like limestone, and permeable rocks which have been highly fractured, it may even reach depths of about 2,000 feet. Generally, however, weathering is confined to depths of 50 feet or so, and is greatest in the zone above the level of the underground water.

Many types of clays are the result of rock weathering, and when these remain in the place they were formed, they are referred to as residual clays. Among the most important of these clays is bauxite, the chief source of aluminium. It is largely a hydroxide of aluminium, $Al_2O_3 . 2H_2O$, but other hydroxides of the metal are also present.

Bauxite deposits were formed on or near the surface by the decomposition, under moist tropical or sub-tropical conditions, of clays resulting from the weathering of clayey limestones and of igneous rocks high in aluminium silicates. Under favourable atmospheric conditions, and probably aided by bacteria, the clay has been robbed of its silica content and there has been concentration of the alumina. The occurrence of large deposits of bauxite in temperate regions in the U.S.A., France, Hungary, and northern Russia is considered by geologists as evidence, supplementary to other criteria, of the prevalence during certain geological periods of tropical or sub-tropical climates in those regions.

The iron ores of the Appalachians, those of Bilbao in Spain, and the famous Cuban iron ores of Santiago are among the residual deposits which owe their origin to the weathering of rocks. Some of the chief manganese deposits of the world, such as those mined extensively in India, the West Indies, and Africa were also formed by a similar process.

Residual deposits may also be developed by the decay of rocks caused by *ascending* solutions. The chief economic deposits of this kind in Great Britain are the famous china-clay deposits of Cornwall and Devon. Before the second world war, our domestic production of china-clay was between 700,000 and 800,000 tons annually, with approximately 50,000 tons of mica-clay as a by-product. It will surprise many to learn that in tonnage of raw material exported from this country, china-clay is normally second only to coal.

China-clay is the product of decomposition of felspar, one of the principal constituents of granite, and of certain highly felspathic sandstones (arkoses) such as those of the Pilsen kaolin deposits of Czechoslovakia. A common felspar in granite is orthoclase, $KAlSi_3O_8$. During its decomposition to form china-clay, or kaolin, $Al_2Si_2O_5(OH)_4$, the potash content and some of the silica has been leached out with the result that the felspar, which can only with difficulty be scratched with a knife, is changed into a soft white clay which has many industrial uses, notably as a filler for paper, rubber, and textiles, and for the manufacture of pottery.

The decomposition of the felspar may be caused by descending surface waters, as in the case of the U.S.A. kaolin deposits and some others, including some of the superficial occurrences in Cornwall and Devon. This kind of decomposition has misled many authorities into believing that *all* china-clay deposits are the result of surface-weathering. We doubt, however, if this theory is accepted for the West of England deposits by any geologist who has made a close study of our china-clay pits. On the contrary, the evidence in support of the theory that in Cornwall and Devon the main kaolinization has been caused by ascending hydrothermal solutions containing carbonic acid, is particularly strong. The whitest and best china-clay is obtained from the deepest pits, some of them 340 feet deep, and the kaolinization in many instances extends considerably *below* masses of overlying unkaolinized granite on which buildings were erected before it was realized that in the clay areas solid granite on the surface often gives place in depth to valuable china-clay deposits.

Deposits formed by Concentration of Substances by Circulating

Waters. Waters of atmospheric origin during their passage downwards through the rocks become charged with small amounts of the carbonates of calcium, sodium, magnesium, potassium, and of iron and other metals, and also with silica. The dissolved salts may be deposited in open cavities and along fissures in the rocks during the descent of the waters and changes may occur in the solutions which give them renewed activity. The waters which return towards the surface after what may be a long and circuitous journey to depths of hundreds of feet can thus become heavily charged with soluble salts. These may be precipitated owing to falling temperature, by reaction with other surface waters, or by absorption of the water into the surrounding rocks. In this way, valuable mineral deposits may be formed.

Certain basic and ultrabasic igneous rocks rich in magnesium silicates alter readily under suitable conditions to yield valuable minerals of economic importance, such as magnesite, talc, and asbestos. Magnesite, $MgCO_3$, one of the chief sources of magnesium, can be formed by one of two main processes, some important deposits being due to the action of infiltrating carbonated waters on serpentine, a rock formed by hydration of certain magnesian silicate rocks. Some authorities believe that the carbonated waters were circulating waters of atmospheric origin, but others maintain that they were hydrothermal solutions emanating from an igneous source. Similarly, different views are held concerning the origin of the solutions which produced talc (or 'soapstone' as it is called when in a massive and impure form) and asbestos by decomposing the rocks in which they occur.

Some barytes deposits result from the concentration, as barium sulphate, of the barium leached from rocks by circulating waters, but many veins of barytes were formed from ascending thermal waters of igneous origin.

Vanadium, some uranium, and a trace of radium, occur in the mineral carnotite, a potassium-uranium vanadate, in certain Jurassic sandstones in Colorado and Utah, in the U.S.A. The carnotite is present usually as a bright-yellow crystalline powder in beds and in fossil wood. The ores are not rich and contain only from 1·5 to 3 per cent of UO_3 and 3 to 5 per cent of V_2O_5. They were formerly worked on a larger scale than at present. Their origin is doubtful, but some geologists think they were concentrated by circulating waters which derived their material by leaching from neighbouring rocks.

The copper deposit of the cupriferous shale ('Kupferschiefer') of Mansfeld in central Germany, which has been worked almost continuously for about 800 years, occurs as a thin bed less than a yard in thickness and is covered by a marine limestone. Many authorities believe that the copper minerals were deposited in a shallow sea into which flowed copper-bearing waters from an eroded mineralized area. Others do not accept this view, and have produced strong evidence in support of the theory that the copper was transported by mineralizing solutions from an igneous source, thus assigning to the Mansfeld deposits the same genesis as that established for most of the world's copper deposits.

SECONDARY CHANGES IN MINERAL DEPOSITS

Many mineral deposits have undergone considerable changes since they were first formed. These changes have been caused mainly through the agency of descending surface waters and are termed 'supergene changes' to distinguish them from the 'hypogene' effects produced by ascending hydrothermal solutions.

At and near the surface the waters are usually rich in free oxygen and contain carbonic acid. Unstable minerals like the sulphides of lead and zinc are oxidized to form the carbonates of these metals. The production from many large lead-zinc mines, in their early stages, has been chiefly from these oxidized ores which, in a favourable environment, may extend to depths of a few hundred feet before the primary, or unaltered galena and zinc-blende deposit, is reached.

Oxidation is in most cases confined to the zone occurring above the permanent water level. If certain unstable sulphide minerals are present then changes of great economic importance may persist to considerable depths, especially in highly fissured rocks, in soluble rocks like limestone and dolomite, and under arid conditions where the descending solutions are less diluted by rain water than in wet climates.

Particularly important and interesting are the supergene processes to which some copper deposits have been subjected, with the result that they show characteristic changes from the surface downwards. Usually, the sulphide of iron, pyrite, is present in copper ores. This mineral is very unstable, being easily decomposed by oxygenated waters into the reddish-brown iron mineral, limonite, with the liberation of sulphuric acid. Chalcopyrite, the chief primary sulphide of copper is also unstable. Some of the iron it contains changes to limonite; some of the copper is oxidized into the spectacular green and blue carbonates of the metal, malachite and azurite; and much or all of the copper may be carried downwards in solution as copper sulphate. As this solution descends, the copper it contains may be re-deposited at and below the permanent water level in the form of chalcocite, Cu_2S, and covellite, CuS. These sulphides of copper are much richer in the metal than the original chalcopyrite, for whereas the chalcopyrite contains 34·5 per cent of copper, chalcocite has 79·8 per cent and covellite 66·4 per cent. This process is known as 'secondary sulphide enrichment of copper'.

The outcrop of a copper deposit is thus often composed of a reddish-brown gossan, or 'iron hat'. Below it is a 'leached zone' from which most of the copper has been carried away in solution. Between the leached zone and the underlying water level, the carbonates and the oxide of copper may occur, and they are followed in depth by the most valuable part of the whole orebody, namely that of the zone of secondary sulphide enrichment. This lies immediately above the unaltered, or primary, zone where in general the copper content of the rock, relative to that in the rich zone, is much poorer and often unworkable. These supergene changes in a copper deposit are illustrated in Figs. 48 and 49.

The Form and Structure of Mineral Deposits

The form in which mineral deposits occur depends mainly on their mode of origin, their subsequent deformation as the result of crustal movements, and the changes to which they have been subjected by natural weathering agencies.

Mineral deposits are conveniently divided into two main classes, *syngenetic* and *epigenetic*. Those of syngenetic origin were formed by processes similar, or almost similar, to the processes in operation during the formation of the enclosing rocks, whereas those

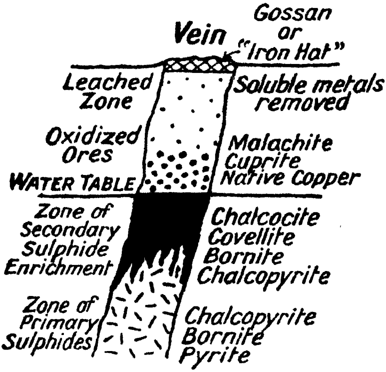

Fig. 48. Weathered Copper Vein, showing zones of oxidation, secondary enrichment, and primary sulphides.

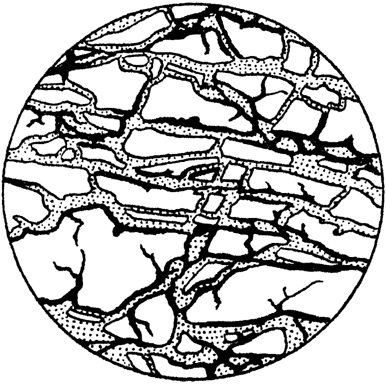

Fig. 49. Polished section showing chalcopyrite (stippled) veining and replacing pyrite (white), and both minerals being replaced by veinlets of secondary chalcocite (black). (Magnification: × 50.)

of epigenetic origin were introduced into pre-existing rocks.

Syngenetic Deposits may be of magmatic or of sedimentary origin. They include concentrations of useful minerals such as magnetite, chromite, and diamonds which have separated direct from the magma, and also sedimentary beds of coal, lignite, gypsum, rock salt, and of many other minerals.

Those which are of magmatic origin may be very irregular in form, but more generally they are somewhat tabular or lenticular, and merge gradationally into the host rocks. They may be wholly in the igneous rock with which they are genetically related or may lie along its margin. They may vary in thickness from a few inches to hundreds of feet, and in length from a few yards to over a mile.

Sedimentary beds were originally laid down as horizontal or nearly horizontal sheet-like flat or lenticular masses, but may subsequently have been folded, overfolded, and faulted by crustal movements. Parallel to their bedding they may extend for many miles, and in thickness may vary from a few inches to hundreds of feet and, exceptionally, to many thousands of feet.

Epigenetic Deposits have a greater variety of forms than the syngenetic deposits, for their mode of occurrence has not been controlled to the same extent by the rocks surrounding them.

Those which have been deposited in fissures in pre-existing rocks occur as *veins*, which are usually steeply dipping tabular masses having a far greater extent in one direction than at right angles thereto. The direction of a horizontal line in the plane of the vein is known as its *strike*; and the vertical angle between a horizontal plane and the plane of the vein, as its *dip*. It is thus evident that the strike and the dip are always at right angles to one another. If a vein has a dip of 60 degrees, its *hade* or *underlie* is 30 degrees, that is, the complement of the angle of dip. A vein or lode may, along its strike, have a length of thousands of feet whereas its thickness may be only a foot or two.

A vein may have well-defined *walls* which separate the mineralized material from the adjacent barren rock. The *hanging wall* is the one above, and the *footwall* the one below, the vein material. The walls may be smooth and separated from the vein by *clay gouge*, or the vein may adhere closely to the wall rock, when it is said to be 'frozen to the wall'.

It is frequently the case that instead of one fissure, there are several parallel or approximately parallel fissures which have been infilled with useful metalliferous minerals to form a mineralized zone. The individual veins may be wide enough to be worked as separate ore-bodies, or they may be narrow and closely spaced to form a *sheeted* or *shear zone* which is mined as one body. The mineralization may have followed narrow, irregular, and discontinuous fissures ramifying through the rock to form a *stockwork*, which is also mined as one mass.

Lenticular veins are of common occurrence, especially in shaley rocks which have been metamorphosed into phyllites or schists. Such lens-like veins may vary in length from a few yards to a hundred or more yards, and their depth is generally much less than their length.

In most mineralized areas the veins have a tendency to occur as *vein systems*. The main series of veins in such a system may have a general strike direction, and another series may be at right angles or at almost any angle to the main series. Two or more veins may coalesce and it is not unusual to find a richer 'shoot' of ore at such a junction.

In some veins or lodes, masses of the 'country rock' —that is the unmineralized rock through which the vein traverses—occur within the vein material. Such masses are known as 'horses'.

If the mineralization has been confined to the fissures, the vein material usually differs markedly in appearance from the wall rocks. Very commonly, however, the mineralizing solutions have been forced into the surrounding country rock and have replaced it for a few inches, sometimes for several feet, beyond the walls by useful minerals. The limit of workable ore may thus not be apparent to the eye and can be ascertained only by sampling and assaying. This is often expressed by stating that the deposit has 'assay walls'.

CHAPTER IX

DISTRIBUTION AND PRODUCTION OF SOME OF THE CHIEF METALLIFEROUS MINERAL DEPOSITS

THE GEOGRAPHICAL distribution of mineral deposits is beyond the control of man. It is governed by geological conditions and is independent of political boundaries. Minerals are obtained from widely scattered parts of the globe and no industrial nation within its own boundaries has sufficient of every mineral raw material it requires.

The vast majority of primary deposits of metalliferous minerals were formed by ascending mineralizing solutions that came from a magmatic source, and they usually occur in close proximity to the igneous rocks with which they are genetically related. These igneous rocks are commonly connected with large-scale crustal folding movements and are spatially related to mountain systems which, in varying degrees, have been eroded by weathering processes. Thus it is that the Andes, the Urals, Caucasus, the Main Granite Range of Malaya, together with mountainous regions now deeply eroded, provide a great deal of the world's gold, silver, platinum, copper, lead, zinc, tin, tungsten, and other metals.

While some parts of the earth's crust are favourable for the occurrence of certain mineral species, others are definitely unfavourable for the same minerals. For example, cassiterite, which yields virtually all the world's tin, is never found in economic quantities except in association with acid igneous rocks of the granite family.

On the contrary, chromite, the only source of chromium, is invariably associated with basic and ultrabasic igneous rocks.

Certain epochs in geological history were characterized by periods of intense mineralization, while others added little to mineral wealth. In pre-Cambrian times there were periods of great addition to the world resources of gold, silver, copper, nickel, iron, and chromium. Between Carboniferous and Triassic times, the tin-lodes of Cornwall, the famous pyritic deposits of Rio Tinto in Spain, and many other notable deposits were formed. During the Jurassic period there were extensive incursions of the sea over many parts of Europe and in some areas there was prolific deposition of oolitic iron ores, such as those of Lorraine, and those of England which stretch southwards from Yorkshire to Northamptonshire. The Tertiary epoch was also a time of intensive mineralization in many parts of the world, giving rise to the formation of the great copper deposits of the United States and Chile, the unique molybdenite ores of Colorado, the silver treasures of Peru, the chromite deposits of Turkey, and the rich gold-silver veins of Nevada.

Some formerly important mining districts are now derelict, others have passed their zenith of production and are approaching exhaustion. There are, however, numerous mining fields still in their early stages of development, with great potential resources. The shift of producing centres has in general been to districts long known to be mineralized, where numerous mines formerly worked as small independent units have been integrated into major undertakings operated by modern mechanical means.

The distribution and production of some of the principal metalliferous deposits of the world are outlined in the following pages under the metal for which they are worked, and the main districts where they occur are shown on the accompanying maps, Figs. 50 to 52.

Aluminium. Although aluminium is present in clays, soils, and many rock silicates, and is the second most abundant metal in the earth's crust, well over 90 per cent of the world supply is obtained from one raw material, bauxite, a rock composed of a mixture of aluminium hydroxides, such as gibbsite, $Al(OH)_3$, and diaspore, $AlO(OH)$. Roughly, four tons of bauxite are required to yield one ton of aluminium metal.

Cheap electrical power is essential for the extraction of the metal, but it is exceptional for such power and large deposits of the raw material to be available in the same country. Thus, Germany and Canada, two of the chief producers of aluminium metal, imported almost all the bauxite they used.

The annual world consumption of bauxite in pre-war days was about 2¾ million tons. France was then the chief source of supply with a yearly production of 600,000 tons; Hungary yielded 350,000 tons; the U.S.A. 300,000 tons; and British Guiana, Yugoslavia, Italy, and Dutch Guiana each about 250,000 tons. During the recent world war the world output of aluminium metal reached a peak of nearly two million tons in 1943, British Guiana being the main source of bauxite supply with a tonnage approaching the two million mark, most of which was exported to Canada for treatment. In addition to the countries mentioned, Rumania, the U.S.S.R., Netherlands E. Indies, Greece, and the Gold Coast contribute important supplies of bauxite.

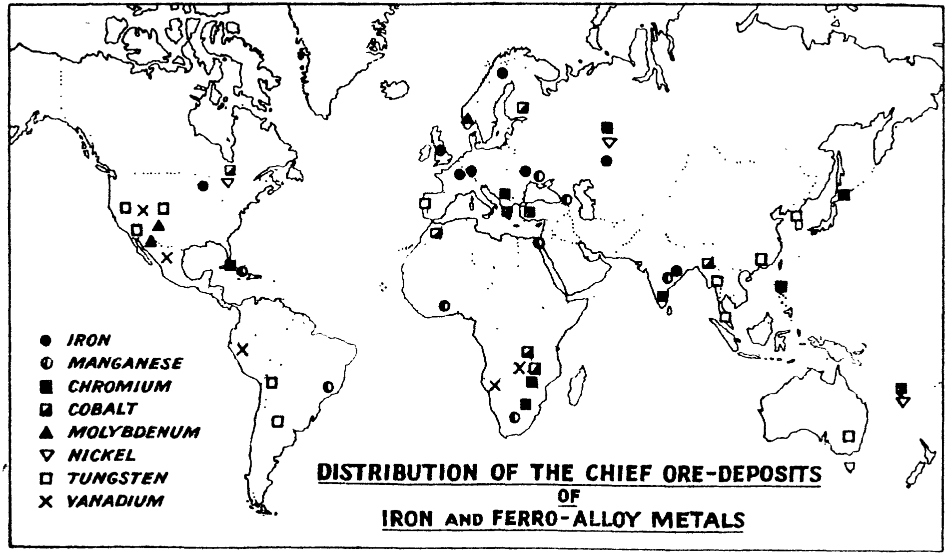
● IRON
◐ MANGANESE
■ CHROMIUM
◩ COBALT
▲ MOLYBDENUM
▽ NICKEL
□ TUNGSTEN
✕ VANADIUM
DISTRIBUTION OF THE CHIEF ORE-DEPOSITS
OF
IRON AND FERRO-ALLOY METALS

Fig. 50.

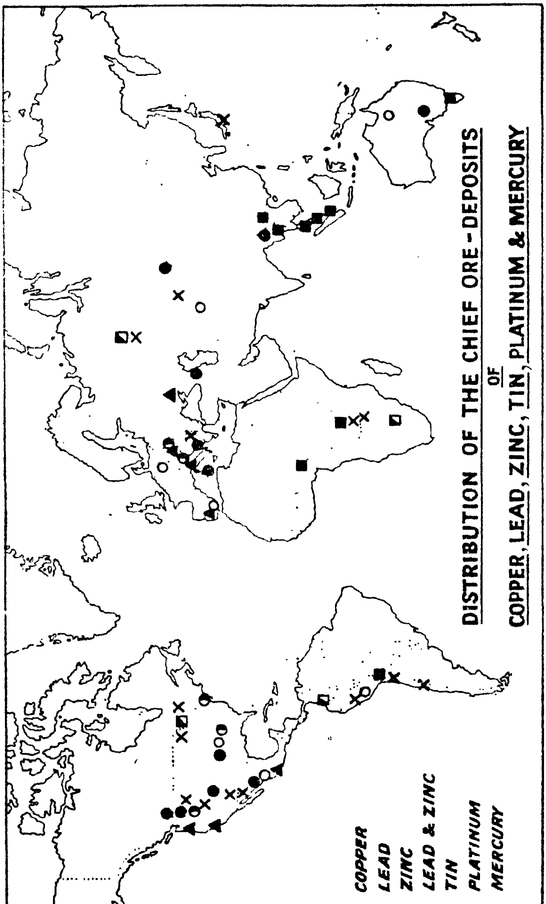
DISTRIBUTION OF THE CHIEF ORE-DEPOSITS
OF
COPPER, LEAD, ZINC, TIN, PLATINUM & MERCURY
× COPPER
○ LEAD
◐ ZINC
● LEAD & ZINC
■ TIN
◪ PLATINUM
▲ MERCURY

Fig. 51.

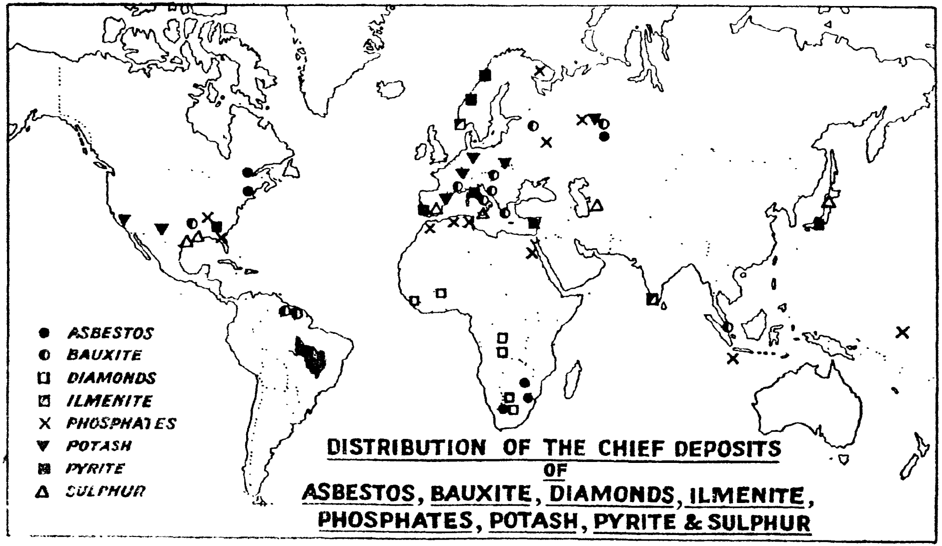
DISTRIBUTION OF THE CHIEF DEPOSITS
OF
ASBESTOS, BAUXITE, DIAMONDS, ILMENITE, PHOSPHATES, POTASH, PYRITE & SULPHUR
● ASBESTOS
◐ BAUXITE
□ DIAMONDS
▨ ILMENITE
X PHOSPHATES
▼ POTASH
■ PYRITE
△ SULPHUR

Fig. 52.

Other aluminium-bearing minerals which are used to a limited extent for the extraction of the metal are leucite, $KAlSi_2O_6$, in Italy; nepheline, $NaAlSiO_4$, and lignite ashes, in the U.S.S.R.; andalusite, Al_2SiO_5, and corundum, Al_2O_3, in Sweden; and alunite, $KAl_3(SO_4)_2(OH)_6$, in the U.S.A. Attempts to extract aluminium from china-clay in the U.S.A. and in this country have hitherto proved unsuccessful.

Copper. The enormous demand for copper during the last three decades stimulated copper mining to such an extent that of the total world production during the past 100 years, more than 75 per cent of the metal has been obtained in the last quarter of a century.

Although copper minerals are very numerous and widely distributed, yet close on 80 per cent of the world supply of the metal comes from four regions, namely, the Rocky Mountain and Great Basin region of the U.S.A.; the pre-Cambrian rocks of northern Michigan and of Canada; the western slopes of the Andes in Chile and Peru; and the Central African plateau of Northern Rhodesia and the Belgian Congo.

For the last half-century the United States of America has been the foremost producing country, and in recent years has yielded about 45 per cent of the world's copper supply. The chief producing centres are in Arizona and the adjacent States of Nevada, Utah, Colorado, and New Mexico. Butte, in Montana, is another important copper field where, within a confined area of 8 square miles, there exists the 'richest copper hill on earth'.

Chile ranks second to the U.S.A., with a production of 15 per cent of the world total. Its estimated reserves of 1,250 million tons of 2 per cent ore in 1936 were the greatest of any country. Chuquicamata, in northern Chile, is reckoned the largest copper mine in the world. The district around Braden, and that near Potrerillos, are the other two main productive centres in Chile.

Canada is third in the list of copper producers, and it is interesting to note that, unlike the production from other countries, the Canadian output is obtained from ores in which other metals, such as gold and nickel, are more important constituents. The yield of Canada is about 12 per cent of that of the world, and is derived chiefly from Sudbury in Ontario, Noranda in the Rouyn district of Quebec, the Flin Flon district of Manitoba-Saskatchewan, and from mines in British Columbia.

Northern Rhodesia, with an output almost equal to that of Canada, has the most important single copper belt in the world. With its proved reserves of about 500 million tons of 4 per cent copper ore it has, within the last two decades, become of outstanding importance as a present and potential source of the metal. The Rhodesian copper belt continues into Katanga in the Belgian Congo, and that country yields about 5 per cent of the world's copper.

Other copper-producing countries are the U.S.S.R., Japan, Germany, Yugoslavia, Peru, Mexico, and Australia, approximately in that order of importance.

For the five years ended in 1938 the average annual world production of copper was 1,750,000 tons, but during the recent war the yearly output reached nearly three million tons.

Gold. Gold occurs in all geological formations, from the oldest to the youngest. It is found in all countries and is present in the waters of seas and oceans. Although so ubiquitous in its distribution, its occurrence in economic quantities is, nevertheless, confined to certain mineralized regions, mainly to those where igneous rocks of intermediate and silicic composition were intruded, and to alluvial and detrital deposits derived therefrom.

Since 1905 South Africa has been the chief producing country. The famous goldfields of the Witwatersrand in Transvaal alone yield more than a third of the world's gold, from a series of quartz conglomerates known as 'banket reefs'. The discovery in the Orange Free State of similar reefs, proved in recent years in bore-holes, may herald the birth of an extremely valuable gold-producing region.

For the five-year period preceding the recent world war, the U.S.S.R. was the second largest producer, yielding about one-seventh of the world total. Most of the gold is obtained from alluvial deposits in the Lena River region, in the Urals, and in the regions of Yakut and Yenessai River. The most productive auriferous lodes are in the Trans-Baikal region in the districts of Belei, Darasun Titagara, and Minussinsk, the Belei mine being the most important.

Canada has for many years contributed much of the world's metal and now ranks third in the list of gold-producing countries, yielding close on one-seventh of the world total. The two chief goldfields are those of Porcupine and Kirkland Lake in Ontario, which together yield about 60 per cent of the Canadian output.

The United States of America, once the second largest source of the metal, now produces somewhat less gold than Canada. Among its many goldfields, the chief ones are those of the Black Hills of South Dakota; the Mother Lode, Grass Valley, and the placer deposits of California; Cripple Creek in Colorado; and Juneau and Nome in Alaska. The most productive mine is Homestake in South Dakota.

In 1941 the total world production of gold exceeded 41 million troy ounces, and in normal times it will again reach and may even surpass that figure. Seventy-five per cent of the total was obtained from South Africa, the U.S.S.R., Canada, and the U.S.A., the remainder being, in order of importance, from Australasia, South America, Japan and Chosen, West Africa, Mexico, Belgian Congo, Rhodesia, India, and other countries.

Iron. Iron is one of the most abundant metals in the earth's crust, and the most indispensable in modern industry.

Although iron-bearing minerals are very numerous, four only of them are important sources of the metal. These are magnetite, Fe_3O_4, hematite, Fe_2O_3, limonite, $FeO(OH).nH_2O$, and siderite, $FeCO_3$.

The world production of iron ore varies considerably with economic conditions and during the last decade has ranged from 140 to 220 million tons, whilst the yearly output of pig iron has frequently exceeded 100 million tons. The U.S.A. has for long been the foremost producer of both iron ore and steel with an output of more than a third of the world total, its pre-war production of steel being more than twice that of Germany, the nearest rival. In recent years the spectacular increase in the U.S.S.R. output has brought that country into second place to the U.S.A. in the production of ore and steel. Prior to the war France produced approximately 16 per cent, Sweden 8 per cent, and Great Britain 6 per cent of the world total of iron ore, with Germany, India, and Luxembourg as other important sources of ore.

Iron ores are formed under various geological conditions and are widely distributed. In the U.S.A. the iron ranges of Minnesota, Wisconsin, and Michigan contain the largest and richest hematite deposits known, and have hitherto supplied about 2,000 million tons of iron ore. Next in importance in the U.S.A. to these Lake Superior deposits are the Clinton ores of Alabama, the third largest producing State.

In central Europe extensive sedimentary deposits of iron ore occur in parts of Lorraine, Luxembourg, Belgium, and Germany. Those of Lorraine are the most productive of all limonitic deposits and in pre-war days yielded annually some 35 million tons of iron ore. Somewhat similar to those of Lorraine are the English Jurassic oolitic iron ores which stretch southwards from Yorkshire through Lincolnshire, Leicestershire, and Rutland to Northamptonshire. The chief mines are near Cleveland in Yorkshire, Frodingham in Lincolnshire, and in Northamptonshire. In 1943 the iron ore production of Great Britain rose to about 20 million tons, more than 90 per cent of which came from the Jurassic ironstones, the remainder being from the hematite mines of Cumberland and Westmorland.

The most productive of all magnetite deposits are those of Kiruna and Gellivare in the north of Sweden. Of the normal annual production of about 12 million tons some 7 millions were exported to Germany and about a third ot that amount to England. Among the extensive deposits in the U.S.S.R. are those of Krivoi Rog in the Ukraine, of Magnitnaya in the Urals, and of the Kuznetsk region in Siberia. Considerable reserves of ore occur also in India, Australia, North Africa, Spain, Norway, Newfoundland, and several other countries.

Lead and Zinc. The most important source of lead is the mineral galena, PbS, and the chief ore mineral of zinc is sphalerite, ZnS, often known as zinc blende. These two minerals, and their oxidation products, frequently occur together and are worked in the same mine. Indeed, there are few mineralized districts where lead and zinc minerals occur as separate orebodies, and in many mines these minerals are also associated with copper ores.

Although small lead mines are widely distributed, the main source of supply comes from relatively few regions and from extensive orebodies. Some of these are approaching exhaustion, and as there have been very few discoveries of notable lead deposits within recent years, the world shortage of the metal will probably stimulate the exploitation of numerous small orebodies serving conveniently sited large central plants.

The normal annual production of lead and zinc ranges from 1½ to 2 million tons of each metal. More than a quarter of the total lead is produced in the U.S.A., mainly from south-eastern Missouri, the Coeur d'Alene district of Idaho, Utah, and the Tri-State area (Missouri-Oklahoma-Kansas). Australia provides about one-seventh of the world's lead output, mainly from the famous Broken Hill district of New South Wales. Canada's yield of approximately one-eighth of the global production is chiefly from the Sullivan mine in British Columbia—the largest individual lead-zinc mine in the world. Mexico produces little less than Canada, principally from the rich lead-silver-zinc deposits near the centre of the country. These four countries together supply about two-thirds of the world total of lead metal.

Other important lead-producing countries include Burma, mainly from the Bawdwin mines; Germany, chiefly from the mineralized Polish-German district of Silesia; and Yugoslavia, notably from the Trepca mine.

Most of the countries and mines which are important producers of lead are also prominent as sources of zinc. Whereas, however, the U.S.A. yields a quarter of the world's lead its output of zinc is in even higher ratio, being about one-third of the total. Most of this production comes from the Tri-State district of Missouri-Oklahoma-Kansas, the greatest zinc region of the world, and the Franklin Furnace area of New Jersey. The deposits of the latter region are unique in possessing a peculiar suite of zinc minerals, not associated with lead minerals and not found in workable quantities in any other part of the world.

Magnesium. During the last few years there has been a rapidly increased demand for magnesium, one of the lightest of all metals, for the manufacture of light alloys used extensively in aeroplanes, motor vehicles, and for many other purposes.

For the five years prior to 1939 the annual world production of the metal was roughly 25,000 tons, more than half of which was made in Germany, the U.S.A., and Great Britain each contributing about 4,000 tons. The insatiable war demand and convenient sources of raw material led to vastly increased production of magnesium in the U.S.A., Great Britain, the U.S.S.R., and Germany, the estimated world output of the metal in 1943 being approximately 250,000 tons.

Magnesium is extracted from the minerals, magnesite, $MgCO_3$; from dolomite, $CaMg(CO_3)_2$; from magnesium chloride obtained from carnallite, $KMgCl_3.6H_2O$; from brucite, $Mg(OH)_2$; from natural brines; and in great quantities from sea-water.

In normal times the annual world consumption of magnesite—which has important uses in addition to being a chief source of magnesium metal—was approximately 2,200,000 tons. The U.S.S.R. production was 800,000 tons, Austria 450,000, Manchukuo 300,000, and the U.S.A. and Greece from 160,000 to 200,000 tons annually. Most of the German production of the metal was derived from magnesium salts obtained from the carnallite-bearing deposits of Stassfurt, and from Austrian magnesite. Considerable amounts of the U.S.A. magnesium is extracted from brines and a large sea-water plant operated in Texas. In some countries magnesite constitutes the chief raw material, and in England and elsewhere a very considerable tonnage of the metal has been produced in sea-water plants.

Manganese. Manganese is one of the most important metals, for not only is it an ingredient of special manganese steels, but it is also virtually essential in the manufacture of all carbon steels.

Almost all the manganese of industry is obtained from two black oxide minerals—pyrolusite, MnO_2, and psilomelane, an impure hydrated oxide of manganese.

For the five years ended in 1938 the annual world production of manganese ore averaged 4,860,000 tons. The U.S.S.R., the foremost producer of the ore since 1929, yielded 2,500,000 tons, or more than all the rest of the world! During the same period, India averaged 750,000 tons, Gold Coast 400,000, South Africa 300,000 tons, and the bulk of the remainder was obtained from Cuba, Brazil, Egypt, and Czechoslovakia.

The two outstanding manganese fields of the world are at Nikopol in the Ukraine, and at Chiaturi (Tchiaturi) in the Caucasus, which together yield most of the great

Russian output. In India, extensive and rich deposits occur in the Central Provinces, Madras, Bihar, Bombay, and Mysore, the principal centres of production being the Balaghat district of the Central Provinces and the Sandhur State in Madras.

During the recent world war, when supplies to the Allied Nations from the U.S.S.R. and India were cut off or seriously impaired, greatly increased productions were exported from South Africa and the Gold Coast. Then the Postmasburg deposits, north-west of Kimberley, yielded annually some 600,000 tons and the Gold Coast more than 500,000 tons.

Nickel. Virtually all the world's nickel is obtained from the two minerals, pentlandite, approximately (Fe,Ni)S, and the green hydrous nickel-magnesium silicate, garnierite.

The annual world production of the metal during recent years has fluctuated between 100 and 150 thousand tons. Canada alone produces about 86 per cent of the global output, the French island of New Caledonia in the South Pacific 8 per cent, and the U.S.S.R. 2 per cent, the remaining 4 per cent coming from numerous minor producing centres. Prior to 1905 New Caledonia was the principal source of supply.

The Canadian output is obtained from the famous nickel field of Sudbury in Ontario, which dominates the world nickel production. In addition to the nickel recovered from the sulphide mineral pentlandite, there comes from the same mines—the chief of which is Frood—a large amount of copper, silver, and selenium, together with most of the world's present yield of platinum metals.

In New Caledonia the nickel mineral is garnierite, which occurs sporadically near the surface in small discontinuous veins and pockets in weathered serpentine rocks.

Nickeliferous sulphide deposits similar in many respects to those of Sudbury, but not so extensive, occur near Petsamo in Finland. These have recently been acquired by the U.S.S.R.

Radium and Uranium. Uranium is not a rare constituent of the earth's crust although workable deposits of uranium minerals are very restricted in their occurrence. Radium, a disintegration product of uranium, is, however, a rare element and is often not present in economic quantities in uranium deposits.

The most important of the uranium minerals is uraninite, UO_2, the colloform variety of which is generally known as 'pitchblende' on account of its pitch-like appearance. Other uranium-bearing minerals include the yellow lime uranite, autunite; the yellow vanadate of uranium and potassium, carnotite; the green copper uranite, torbernite; the orange hydro-uranate of lead, curite; and the black oxide, thorianite, chiefly $(Th,U)O_2$.

The principal radium-uranium deposits of the world are those on the shore of Great Bear Lake in the North-West Territories of Canada. They were discovered in 1930 and within a few years the world's supply of radium was greatly increased and the price, until then controlled by a Belgian company, was lowered considerably. The pitchblende of Great Bear Lake is associated with native silver and with cobalt-nickel arsenides. The concentrates are transported by air to railhead and thence to the refinery at Port Hope in Ontario. Uranium used in making the atomic bombs was obtained from the Great Bear Lake deposits.

Until the discovery and development of these Canadian deposits, the main source of radium and uranium supplies was from the Chinkolobwe mine in Katanga, Belgian Congo. The ores consist of pitchblende and its spectacularly coloured oxidation products, one of which is the deep-yellow mineral curite, named after the discoverer of radium.

The mines of Joachimsthal in Czechoslovakia, made famous as the source of the pitchblende from which Madame Curie first extracted radium, still supply a little radium and uranium from nickel-cobalt veins.

Before the development in 1923 of the very rich uranium deposits of the Belgian Congo, the carnotite ores of Colorado and Utah supplied most of the world's radium and uranium. Those of Colorado are still worked on a small scale for vanadium, with radium and uranium as by-products. Unlike the Canadian and Belgian Congo uranium deposits which were formed by ascending hot mineralizing solutions, those of Colorado are of sedimentary origin.

Pitchblende is known to occur in small quantities in some of the tin-mining districts of Cornwall and Devon, of Portugal and north-west Spain, and minor deposits exist in South Australia, Madagascar, Norway, Sweden, Mexico, Peru, and Argentine. Some years ago pitchblende was extracted from a number of small 'radium mines' in Portugal. Practically no information is available about sources in the U.S.S.R., but uranium minerals are known to occur there.

Recent statistics concerning the world production of radium and uranium have not been released. In 1938 Canada produced 75 gm. of radium and 800,000 lb. of uranium salts; the U.S.A. yielded 8 gm. of radium and

52,000 lb. of uranium; and until 1939 the Belgian Congo production of uranium salts was 50 per cent more than that of Canada.

Silver. Silver occurs in nature in the form of metal and also in combination with other elements, mainly as the sulphide, argentite, Ag_2S, which is a common associate of the sulphides of lead, zinc, and copper. Thus it is that more than half of the world's silver is obtained as a by-product from mines worked chiefly for other metals.

The average annual world production of silver in normal times was between 241 and 242 million troy ounces. A third of this total came from Mexico, which for the last three centuries has been the principal source of the metal. The deposits in Mexico form part of a mineralized belt which extends northwards to Utah and Nevada, and this part of the North American Cordilleras yields about half of the world's silver, the major part of the output being obtained from lead mines. About 25 per cent of the global production came from the U.S.A., the chief States, in order of importance, being New Mexico, California, Arizona, Idaho, Nevada, and Utah.

Canada is third in the list of producing countries and yields about 8·5 per cent of the total, Europe supplying 8 per cent, Peru and Australia each contributing just over 5 per cent, to be followed in turn by Japan, U.S.S.R., Burma, and Bolivia. The Andean region of South America was for long the principal source of silver. It includes the copper mines of Cerro de Pasco in Peru, at present the world's foremost producer of silver, and the now largely exhausted Potosí district in Bolivia, famed as the 'richest hill on earth', which is reputed to have yielded more than 1,000 million ounces of silver since it was discovered 400 years ago.

Tin. The world's supply of tin is obtained virtually from one mineral, cassiterite, SnO_2, only a very small percentage being derived from sulphides of tin which accompany cassiterite in parts of Bolivia.

Workable deposits of cassiterite are restricted to a few parts of the earth's crust. In Canada and the U.S.A. there is not a single tin mine; the whole of Europe yields less than 1·5 per cent of the world total, and more than half the European production is obtained from Cornwall.

The chief tinfields of the world can be resolved into five 'metallogenetic tin provinces', that is, to parts of the earth where tin mineralization with respect to each group or province was effected during the same geological period under similar, or almost similar, conditions. These five groups, with their average annual percentage of world production for the ten pre-war years, 1929 to 1938, are as follows: (i) Malaya, Netherlands East Indies, Siam and Burma, 61·7 per cent; (ii) Bolivia, 18·0 per cent; (iii) China, 5·7 per cent; (iv) Nigeria, 4·9 per cent; (v) Belgian Congo, 2·6 per cent, making a total of 92·9 per cent of the world output. The three outstanding producers are the Federated Malay States, Netherlands Indies, and Bolivia.

The principal sources of tin in most parts of the world, except in Bolivia, are alluvial and detrital deposits where the cassiterite has been concentrated by natural processes. They are surface deposits of limited depth, many of which have already been worked out, others are nearing exhaustion, while some will continue to supply tin for many more years. It is inevitable, however, that the time is not far distant when lode mines, such as those of

Bolivia and Cornwall, will afford the chief source of supply.

The average annual world production of the metal during the five pre-war years 1934 to 1938 was 160,200 tons. During the recent war, when Japan occupied the countries which normally produced two-thirds of the world output, the yield decreased greatly despite intensified production in Bolivia, Nigeria, the Belgian Congo, and in Cornwall.

Tungsten. Wolframite (or wolfram), $(Fe,Mn)WO_4$, and scheelite, $CaWO_4$, are the two chief minerals which yield tungsten, though in some parts of the U.S.A. the minerals ferberite, $FeWO_4$, and hubnerite, $MnWO_4$, are also sources of the metal.

Prior to 1918, the Tavoy district in Lower Burma and the Mawchi mines (the largest of all wolfram mines) in Upper Burma were the principal centres of wolfram production, but later discoveries of the mineral over extensive districts in Kwantung, Kiangsi, and other parts of China, established that country as the foremost source of supply. Bolivia and Portugal are also important producers of wolfram, the Panasqueira mine in Portugal being the second largest of its kind in the world.

The main scheelite-producing countries are the U.S.A. and the Federated Malay States.

For the quinquennial period ended in 1938, the average annual world production of tungsten, in terms of metal, was about 13,000 tons, the output in 1938 exceeding 36,000 tons of concentrates containing 60 per cent of tungstic oxide, WO_3. It has been well stated that 'the more tension the more tungsten', and intense efforts were made during the recent war to increase production of the metal. In normal times the percentage of the world supply of tungsten from China was 33 per cent, Burma 20 per cent, Portugal and the U.S.A. each 11 per cent, Bolivia 9 per cent, Japan 4·5 per cent, whilst Argentina and Australasia contributed respectively 3·4 per cent and 2·7 per cent of the total.

CHAPTER X

THE SEARCH FOR MINERAL DEPOSITS

CHANCE HAS played a dominant role in the discovery of mineral deposits, and the history of many mining fields opens with the accidental finding of a fragment of ore or the outcrop of a lode. Even the prosaic stubbing of a toe against a protruding rock has sometimes had a lucrative recompense! The discovery of a shining stone by a child playing on the banks of the Orange River in 1867, and a shepherd-boy's find of a perfect white diamond, led to the development of the Kimberley diamond mines and the industrial awakening of South Africa. Potosí, in Bolivia, was discovered 400 years ago when a llama uprooted the bush to which it was tethered and thereby exposed a vein of native silver. Forty years ago a man in charge of a llama pasture in the high Andes of Peru complained bitterly of the poor quality of his only available fuel, a black asphaltic substance that lay near his hut. Analysis proved it to be rich vanadium ore, and the pasture of Minasragra has since developed into the world's principal source of vanadium. Nickel was first identified in the Sudbury district of Ontario in 1856, but it was twenty-seven years later that a blacksmith working with a construction gang on the Canadian Pacific Railway noticed glistening patches of yellow metallic minerals in a fresh cutting, and attention thus became focused on an area which has since produced nearly 90 per cent of the world's nickel output.

The fabulously rich silver veins of Cobalt in Northern

Ontario were also discovered accidentally during the building of a new railway. Specks of gold fortuitously exposed in the tail-race of a sawmill led to the great Californian gold rush of 1849, and the famous lead-zinc-silver ores of Broken Hill, New South Wales, were found about sixty years ago by boundary-riders who mistakenly imagined they had struck a tin lode. Drilling for water has been a fruitful means of locating buried orebodies, including the great lead-zinc deposits of Oklahoma. Ancient prehistoric workings are an unfailing attraction to the prospector, and many modern mines, such as those of the Kolar goldfield in India, the Lake Superior copper belt, and the Bawdwin silver-lead-zinc area of Burma, have been developed on or near the site of long-abandoned diggings.

Credit for finding most of the orebodies which have been worked during the past hundred years belongs to the indomitable old-time prospector. With his pick and shovel, hammer and pan, he has roamed the desolate places of the earth in search of his El Dorado, lured on by a fortune at the rainbow's end. Scores of mining districts, including the most productive goldfield in the world, that of the Witwatersrand in the Transvaal, owe their beginning to his perseverance and skill. By his widespread activities he has probably found most of the rich orebodies that are exposed at the earth's surface. Outcropping mineral deposits will doubtless be located in the future in unexplored areas of the globe, but the chances of making such discoveries grow smaller. Indeed, it becomes increasingly difficult to find new deposits without recourse to scientific prospecting based on geological knowledge. Nowadays the diminishing number of 'practical prospectors' usually work under the supervision of geologists, and many mining organizations employ specially trained geologists for systematic areal prospecting and for directing exploration work on the surface and underground.

Among the more obvious clues for which the prospector searches is 'float', that is, fragments of mineral or vein-matter that have been broken by frost or other weathering agencies from the outcrop of an orebody. By careful examination these tell-tale fragments, often consisting of hard rust-stained quartz, may be traced uphill to their original source. In northern latitudes it is sometimes possible, by determining the direction in which a long-vanished glacier travelled, to trace the source of glacial erratic boulders containing valuable minerals; by this means a rich gold-copper deposit was recently discovered in Sweden.

When heavy insoluble minerals such as gold, platinum, tinstone, and most precious stones, are released from their matrix by chemical and mechanical weathering, they are washed slowly downhill and are eventually concentrated by streams as placer deposits. Flowing water sweeps away the lighter material and the heavier minerals sink to the bottom or are carried slowly downstream, tending to accumulate wherever the velocity of the water is checked. In the case of gold the particles usually become flatter and more flaky the farther they have been transported from their original source.

It is not surprising that the art of panning alluvial gravels dates back to ancient history, for with the aid of a shovel and washing-pan a man may sometimes win a fortune in the space of a few weeks. The finding of valuable placers has resulted in some of the spectacular gold and diamond rushes of the world. To discover the source of the placer minerals the prospector proceeds upstream until the minerals fail to show in the pan; he then ascends the adjoining hillslopes or a tributary creek until panning tests yield no further trace of the sought-for materials, a fact indicating that he has overstepped their original source. Haply he may find thereabouts a few fragments of mineralized rock or a series of rust-stained boulders, and by trenching ('costeaning') encounter the broken mother lode. An old method of exploring for veins on hillslopes is that of 'hushing', formerly much practised in the North of England when searching for lead and zinc. It consists in impounding water at a high level and then releasing it suddenly so as to scour the cover of soil from the hillside. This is analogous to 'hydraulicking', whereby the surface is stripped and laid bare by powerful jets of water, a procedure which met with singular success at Cobalt in Ontario by exposing several mineral veins, one of them yielding 27,000 ounces of silver from shallow workings. In the absence of water the prospector may have to rely upon the wind to aid him by its winnowing action by blowing the finer and lighter material to leeward as it falls through the air, thus separating the heavier valuable minerals. Suitable repetition of the process frequently provides a rich concentrate. This method proved to be of great value in the early exploration of the parched goldfields of Western Australia.

In the search for ore deposits there are few more arresting and encouraging signs than the reddish 'iron hat' or 'gossan' that represents the weathered outcrop of a mineral deposit containing iron-bearing sulphides (Fig. 48). During long-continued erosion sulphur, copper, and other soluble metals, are leached from the exposed sulphide minerals and carried downwards by percolating waters, leaving behind at the surface a cellular mass of rusty iron oxides consisting mainly of limonite. The finding of such a limonite capping may therefore herald the discovery of an underlying valuable metalliferous deposit. On the other hand, it may only raise false hopes, for many gossans represent merely the oxidized roots of a vanished orebody or the outcrop of thin non-commercial sulphide veins. Wide experience and geological acumen is required to interpret the full significance of the tell-tale colour variations, structure, and extent of gossans. In some cases, as at the famous Rio Tinto mines in Spain, the red gossans form conspicuous landmarks crowning the hilltops and have attracted attention from the earliest times. Many of them are extraordinarily rich in native gold and silver, and were worked by the ancients for these precious metals. Among other colour signs for which the prospector is on the alert are the vivid greens and blues of oxidized copper minerals, the sooty black stains of manganese, the 'blooms' of cobalt and nickel, respectively brilliant pink and apple-green, and the yellows of arsenic and molybdenum compounds.

These conspicuous signs of mineralization are a windfall to any prospector, but the trained geologist relies more in his methodical search for ore on a knowledge of the geological conditions favourable to mineralization. By careful mapping he deciphers the geological history of an area, and by studying the structural features of the rocks and the interrelationship between igneous and sedimentary types he is able to localize intensive examination to the most promising districts. Many mineral deposits are concealed beneath a thick mantle of overlying rocks, and only by sound geological reasoning can their position be predicted with any degree of assurance. Among the growing number of important achievements due to scientific prospecting by geologists are the discovery of the great copper deposits of Northern Rhodesia, which contain more than 750 million tons of high-grade ore, the immense manganese orebodies of the Gold Coast, and the extensive rich bauxite deposits of British Guiana. Recently, hundreds of geologists have been engaged in prospecting for minerals essential for the war effort, and many valuable discoveries have been made, especially in the Soviet Union and South America. Indeed, the amazing development of mineral resources in the U.S.S.R. during the past two decades is due in considerable measure to the successful explorations undertaken by Soviet geologists.

In attempting to assess the possibilities of future mineral discoveries it should be realized that over most of the earth's surface the 'solid' rocks are buried beneath a blanket of glacial clays and sands or by residual products of weathering. Moreover, mineral deposits formed in earlier geological periods are commonly concealed by a thick covering of younger sediments and volcanic rocks. Important bodies will undoubtedly still be found exposed at the surface in unexplored regions of the globe, but discoveries of the future will come increasingly from deep exploration in areas of known mineralization and from those vast tracts where the cover of overlying rocks virtually precludes the location of buried mineral deposits by ordinary methods of geological investigation.

Happily, during the last twenty-five years or so a new method of exploration, that of *geophysical exploration*, has come to the aid of geologists in the quest for hidden mineral deposits and for the elucidation of concealed geological structures. This scientific method of prospecting, which supplants the magic of the witch stick and divining rod, has already achieved remarkable successes, especially in oilfield exploration, and will unquestionably be used increasingly in the future search both for metalliferous and non-metalliferous deposits. The essential requirement in all branches of geophysical prospecting is that there should be a well-marked difference in certain physical properties, either between the mineral deposits and their enclosing rocks, or between adjacent geological formations when structural problems are being investigated. It must be emphasized that these methods are primarily concerned with detecting differences in the physical properties of the rocks, and seldom claim to reveal directly the presence or exact nature of a mineral deposit. To interpret effectively the results obtained by geophysical surveys, it is almost invariably essential that the geologist and geophysicist should work in close collaboration.

In the search for mineral deposits other than oil, the principal methods used are magnetic, electrical, and electromagnetic. The gravitational, seismic, and radioactive methods have been hitherto usually reserved for oil exploration and special problems in connexion with the location of particular orebodies.

It has long been known that *magnetic* deposits disturb the earth's magnetic field in their vicinity, causing local deviation of the compass needle. Indeed, magnetic methods of locating iron ore were used successfully in Sweden 300 years ago, and have been employed in the Lake Superior region for more than half a century in the search for copper-bearing basaltic lavas and iron deposits. Rapid surveys can be made with a compass, and with a dip needle which is free to rotate about a horizontal axis and has a counterweight attached to its south side to compensate for the vertical component or 'inclination' of the earth's field. For more accurate work, however, delicate instruments known as magnetometers and variometers are generally favoured. These instruments are capable of detecting buried deposits of magnetic iron ore, nickeliferous pyrrhotite and cobalt ores, and are of great service in mapping the underground distribution of igneous and sedimentary rocks rich in disseminated magnetite. Indirectly they serve to locate alluvial deposits of gold and platinum which happen to contain abundant grains of magnetite or which lie in valleys beneath younger flows of basalt.

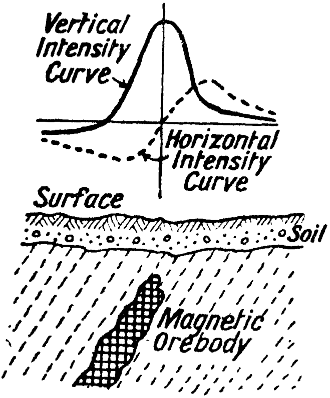

Fig. 53. Profiles of horizontal and vertical components of magnetic field across a magnetic orebody.

Two outstanding examples of magnetic iron ore explorations are those of the Kursk magnetic anomaly in the Russian Ukraine, where colossal iron ore reserves were proved, and of the world-famous magnetite deposits of Kiruna in Sweden. Forty years ago the celebrated inventor Thomas A. Edison designed a magnetometer. After first testing it over a known nickel-pyrrhotite deposit at Sudbury, Ontario, he obtained strong indications of ore whilst prospecting a few miles away, at Falconbridge. Unfortunately, the small shaft then sunk had to be abandoned in quicksand at a depth of 80 feet, but many years later a slightly deeper shaft at the same site reached the rich Falconbridge orebody. By mapping certain magnetic shales which underlie the main gold-bearing reef of the Witwatersrand in South Africa, magnetometer surveys have recently indicated the extension of the gold-field for many miles to the west, and similar investigations have resulted in the location of diamond-bearing igneous plugs or pipes in South and East Africa. Typical anomalies in vertical and horizontal intensity over a concealed magnetic orebody are depicted in Fig. 53.

Electrical methods of finding ore deposits depend upon the marked difference in electrical conductivity between metalliferous minerals and the surrounding rocks. Most ore minerals which possess a metallic lustre, such as the sulphides of iron, copper, and lead, conduct electricity many thousands of times better than the rocks enclosing them. The natural current (self-potential or spontaneous polarization) method of locating sulphide deposits is unique among electrical methods in that no currents are artificially introduced into the ground, the orebody itself acting as a battery which produces current detectable at the surface by means of a sensitive microammeter or potentiometer. Due to vigorous oxidation the upper part of the deposit is chemically more active than the lower, the resulting electro-chemical conditions thereby inducing positive polarity at the top of the body and negative polarity at the lower extremity. Currents thus flow down the orebody and complete a circuit by returning upward through the surrounding rocks, as shown in Fig. 54. At the surface the lines of current tend to flow in towards the ground immediately above the orebody, known as the 'negative centre'. This centre can be found either by tracing lines of equal potential or by determining the direction and magnitude of the currents.

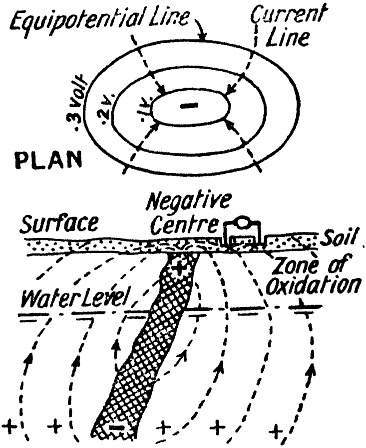

Fig. 54. Natural currents produced by an oxidizing sulphide orebody. Plan shows curves of equal voltage, and current flowing towards the negative centre above the orebody.

In most electrical methods of prospecting, direct or alternating current is introduced artificially into the ground between a pair of earthed electrodes, and conducting orebodies are located by means of potential observations made at the surface. The lay-out for a simple method, known as the equipotential method, of which there are many variations, is depicted in Fig. 55. Two bare copper or iron wire electrodes, AB and CD, each about half a mile long, are pegged to the ground at short

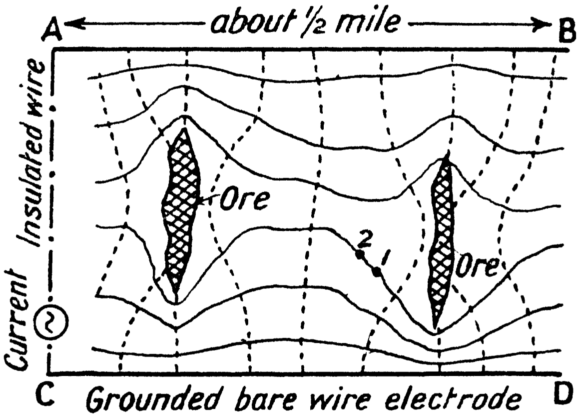

Fig. 55. Equipotential survey using parallel linear electrodes. Current lines, dotted; equipotential lines, continuous.

intervals and connected by insulated cable to a generator. When current passes between the two electrodes, the lines of flow crowd in towards any mass of conducting material, as indicated by the dotted lines, and the equipotential lines, which are always perpendicular to the direction of current flow, diverge from the conductive body as shown by the continuous lines. To detect the presence of a concealed conductor, such as an orebody, equipotential lines are traced out on the ground by means of a simple portable circuit consisting of two sharp metal rapiers, connected by about 100 feet of insulated flexible wire to a pair of earphones. One rapier is thrust into the ground and the operator moves forward making trial contacts with the other rapier in order to find the equipotential point, which is located when the note or buzz of the generator is no longer heard in the earphones. The two points (e.g. 1 and 2 in Fig. 55) are then marked by pegs and the procedure repeated until a continuous equipotential line is run across the area. For general reconnaissance and for detecting sulphide bodies buried at shallow depth this method has often proved quite effective. It met with spectacular success, for instance, at the Buchans mine in Newfoundland by discovering a large lead-zinc-copper deposit, and in northern Sweden by locating several rich gold-copper-arsenic bodies, the bodies in both countries being buried beneath glacial clays and sands.

Since most metal sulphides are good conductors they may frequently be found by using electrical methods involving the measurement of *earth-resistivities*. Four ground electrodes are spaced equally in a straight line and current is passed between the two outer ones, C_1, C_2 (Fig. 56), the resulting voltage set up between the two inner electrodes P_1, P_2 being measured with a portable potentiometer, V. Close spacing of the electrodes permits only a shallow sub-surface current penetration, but with increasing electrode separation the current reaches greater depths. In making measurements, traverses may be made using a constant electrode separation so that the area is examined to a fixed depth, or the electrode system may be expanded about a particular point in order to determine the change of resistivity with increasing depth.

Resistivity is at a minimum when the two inner potential electrodes are above the conductive orebody. This method provides a simple means of detecting concealed low resistivity deposits and of ascertaining their depths beneath the surface.

Both for general reconnaissance and especially for intensive investigation of areas suspected of mineralization, various *electromagnetic* methods are widely favoured, for they yield much detailed information concerning the shape and position of hidden conductors. For instance, when alternating current is passed through a large horizontal loop of insulated cable suitably disposed on the ground, electromagnetic waves spread out in all directions from the energizing loop. These waves stimulate currents by induction in any conductive body which is

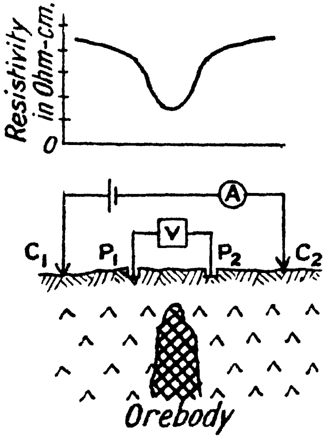

Fig. 56. Electrical resistivity method. Curve shows drop in resistance due to a conductive orebody.

present, causing it to re-radiate a secondary induced field whose effects can be examined at the surface by portable search coils. Among the many advantages of this inductive method is its efficacy in mountainous regions, in deserts and in frozen snow-laden areas, over ice-covered lakes, and in districts covered by non-conductive surface rocks. The large gold-copper-arsenic orebody at Boliden, in northern Sweden, was discovered largely by electromagnetic surveys.

Gravitational methods of prospecting depend on the differing densities of rocks, which modify the magnitude and direction of the earth's gravitational attraction. Thus, a heavy orebody will attract and deflect a pendulum, besides causing it to swing more quickly. The two chief types of instruments used are the gravimeter, or gravity meter, which utilizes the elastic force of springs and the torsion of wires for direct comparison with gravity; and the torsion balance which measures the rate of change of gravity per unit horizontal distance. They have been used extensively in oilfield exploration for locating favourable geological structures such as buried anticlines (arched folds) and salt domes. With the exception of certain gravimetric surveys over shallow orebodies, these instruments have hitherto had only a limited application in prospecting for ores and nonmetallic deposits, though there can be no doubt that the highly sensitive modern gravimeters will in future find greatly increased service in this particular field.

The *seismic* method of exploration depends upon the speed with which artificial earthquake waves travel through rocks, the velocity being dependent upon the elasticity and density of the various formations. Thus, in igneous, metamorphic, and salt formations the waves travel several times more quickly than in loosely consolidated clays, sands, and marls. Waves set up by firing a charge of buried explosive are automatically recorded on a series of portable seismographs, and since the depth of penetration of the recorded waves is directly related to the spacing between the shock point and the vibration detectors, the variations of physical properties of the rocks with their depth may be measured. In the 'reflection' method, the time required for waves to travel to and from a reflecting bed, such as a massive limestone, is measured in order to calculate the depth to the reflecting surface. In the 'refraction' method travel-times of the first impulses to arrive at the detectors are observed. Since waves usually travel faster in the deeper layers, beyond a certain distance from the explosion point waves which descend to a high-velocity bed and are refracted along it will actually reach the recording instruments before the slower surface waves travelling by the direct and shorter route. This critical distance, supplemented by a knowledge of the velocities in the upper and lower beds, enables the depth to the boundary to be determined. Seismic prospecting has been used with remarkable success in oilfield exploration, by revealing subsurface geological structures and the presence of salt domes, and immense quantities of oil have been discovered by means of it. In mining exploration, however, seismic methods have so far had only limited application, as in determining the course and depth of gold and diamond placer gravel channels, the location of sulphur deposits above salt domes, and the structure of certain coal and lignite deposits.

Following the recent startling revelation of released atomic energy there is sure to be rapid intensification in the search for *radioactive* elements, such as uranium and thorium, which emit radiations by the breaking down or disintegration of their atoms. Radium, one of the intermediate products in the spontaneous disintegration of uranium, itself breaks down by the loss of an alpha particle, or helium atom, into the heavy inert gas radon (radium emanation). This gas is of special importance in radioactive methods of prospecting because it disintegrates slowly and can be readily detected by means of a portable gold-leaf electroscope, the rate of movement of the leaf being proportional to the quantity of radon present. Radioactive exploration can be carried out by taking soil or rock samples and testing them in the laboratory, or by determining the activity of rocks in situ with portable ionization chambers, such as the open-bottom type and the Geiger-Muller counter, which measure the intensity of penetrative gamma radiation being emitted. Radon migrates from its birthplace, is absorbed by oil and water, and tends to collect along faults, fissures, contacts, and beneath impervious wet clays, so that anomalies due to such local accumulations of radioactive products may exceed those due to the presence of uranium ores. With increasing distance from a radioactive deposit activity diminishes rapidly, and it is recorded that the pitchblende deposit of Joachimsthal in Czechoslovakia could not be detected at distances exceeding 1,000 feet. Hitherto, radioactive prospecting has been of greater service in detecting local concentrations than for discovering radioactive ores by reconnaissance, though we may be sure that the urge to find such ores will result in great technical improvements in this method of prospecting. Indeed, it may soon become practicable to reconnoitre by measuring the intensity of gamma radiation whilst flying across an area in a helicopter.

There can be no doubt that as the finding of new mineral deposits by ordinary geological methods becomes more difficult the demand for geophysical exploration as an aid and supplement to geological surveying will continue to grow.

CHAPTER XI

THE EXTRACTION OF MINERALS AND METALS

THE METHODS by which minerals are won from the ground depend on many factors, the chief being the nature and form of the deposits and the position they occupy relative to the surface.

Some stable minerals like those of gold, platinum, tin, and precious stones remain unaltered in sands and gravels and can be won readily by washing away the lighter and valueless material with which they occur. Others, like the minerals which yield lead, zinc, copper, &c., are not usually found in economic quantities in sands and gravels because their physical and chemical properties render them unsuitable for preservation during and after transportation in running water. Stable minerals remain unaltered also in rocks which have weathered in situ on the surface, while the less resistant minerals are decomposed to form new and often useful minerals in the weathered rock, or some distance away from their original home, by precipitation from solutions. Many of the most important mineral deposits however occur well below the surface and the rocks in which they occur have to be drilled, blasted, crushed, and ground to fine particles to yield the required minerals.

We can thus consider mining operations as being broadly of two kinds, namely *surface mining*, which includes the working of sands and gravels and of hard rocks by open-cutting or opencast methods, and *underground mining.*

Surface Mining Methods. The extraction of rocks on the surface for building and road-making is usually termed quarrying. There is however no sharp distinction between quarrying and mining. In general, quarrying is the term applied to the extraction of rock used in virtue of its bulk and other physical properties, whereas if the extracted material is subjected to treatment to obtain one or more of the minerals it contains, the operations come under the category of mining. Quarrying methods are so familiar to readers that we need not consider them further.

The simplest and one of the oldest forms of mining is the washing of sands and gravels containing valuable minerals. It is a fortunate provision of nature that in almost all such occurrences, the valuable minerals have a higher specific gravity than the great bulk of the alluvial deposit. Sands and gravels, for example, consist mainly of quartz which has about a third of the density of the tin mineral, cassiterite, and only a small fraction of the density of native gold and platinum. These heavy minerals can thus be won easily in swiftly flowing water ('streaming') which carries away the clay and quartz, leaving behind concentrations of the valuable minerals. Similarly, by swirling the water in a pan ('panning') the same result is obtained. Where water is not available, as in arid regions, concentrations of the heavy minerals can be effected by winnowing in moving air.

A great wealth of minerals has been obtained from loose surface deposits since earliest times, and even to-day alluvial deposits contribute most of the world's tin and a great deal of its gold, platinum, diamonds, and other precious stones. The simple methods of the past have been replaced in modern times by highly mechanized means which have brought extensive low-grade deposits, formerly unworkable, within economic limits and thus have increased greatly the world's available mineral resources.

The choice of method for working loose surface deposits depends on the amount of valuable minerals present; the extent, depth, and nature of the material; the thickness of the barren ground ('overburden') covering it; the nature of the bedrock on which it rests; and on the topographical situation of the deposit.

If the thickness of the overburden is not too great for surface mining, the barren ground is removed by bulldozers, mechanical excavators, and drag-line dredgers, and the exposed valuable deposit may be excavated by similar means. In opencast coal mining, for example, a wide trench or swath is made through the overburden by steam or electric shovels and the exposed underlying coal removed mechanically. A parallel swath is then cut and the overburden dropped where the coal has been removed. In this way a series of parallel and adjoining swaths are made, the coal is excavated, and a new surface is formed.

In some parts of the world, minerals of economic importance occur on the flanks of hills and mountains where the rocks have lost their coherence as the result of weathering agencies. These are usually worked by open-cutting, or as opencast mines. Deposits of this type yield a great deal of the world's iron, manganese, copper, and aluminium. They are usually worked in the form of spiral terraces several feet in height, and the material is removed by mechanical shovels into trucks and transported to the concentrating plants for treatment. If parts of the deposits are too coherent for the excavators, they are first drilled and blasted on a large scale to loosen the ground. Chuquicamata, in Chile, the largest copper mine in the world, is worked in this way, and so are several mines in the U.S.A. and other countries. At Bingham, in Utah, U.S.A., 95,000 tons of copper ore and a quarter of a million tons of waste rock are removed daily!

Another form of opencast mining is known as 'glory-holing'. The broken rock is dropped to a lower level through ore passes, trammed to the shaft bottom, and hoisted to the surface. In form, the glory-hole is somewhat like a gigantic funnel, the neck being the ore pass, not the shaft. The bottom of the shaft is usually reached through a connecting tunnel.

In Malaya, the Netherland East Indies, Nigeria, and other countries where tinstone occurs extensively in alluvial and eluvial deposits, much of the cassiterite is obtained by hydraulicking, a method used also for some gold-bearing surface gravels. A large volume of water is conveyed through pipes from a source higher than where it is used in order to obtain the required natural pressure. A nozzle is fixed at the end of the pipes and the resulting powerful jet of water is directed against the face of the gravel. The arrangement is not unlike that used by firemen when directing water on to a burning building. The released gravel is then sluiced through channels, or through troughs, where the tinstone or gold is trapped at the bottom in riffles. Such a method requires an adequate supply of water under a natural head and the provision of lower-lying ground where the bulky valueless material ('tailings') can accumulate.

The mineral-bearing deposits are often situated, however, in low-lying and sometimes marshy ground unsuitable for hydraulicking. If the alluvium is sufficiently extensive to warrant the capital expenditure, it may be worked by dredging. The dredger is usually erected on the ground in an artificial pond ('paddock') and the gravel is excavated by a number of large steel buckets linked to a long boom or 'ladder' (not unlike the arrangement in a harbour dredger) which can be lowered to considerable depth. The elevated gravel is passed through a rotating trommel where it is played upon by a powerful jet of water and screened. The tinstone or gold is in the finer screened material which drops into long shallow troughs erected on the deck. The heavy minerals sink to the bottom and are trapped by the riffles. Concentration of the heavy minerals may also be effected by employing the hydraulic jigs with which some modern dredgers are equipped.

Underground Mining Methods. There are so many methods of underground mining that the most that can be attempted here is to outline the most important of those in common practice.

One of the first essentials in underground mining is to make an entry into the orebody. If the topography is suitable, as on hilly ground, a tunnel ('adit') may be driven into it through the hillside. The adit may serve for mine drainage and for transporting the ore and waste to the surface. In the largest lead-zinc mine in the world, Sullivan mine in British Columbia, the ore is transported through a single adit thousands of feet in length. Most orebodies are, however, reached through a vertical shaft, and in fewer cases through an inclined shaft.

The shaft may pass through a series of orebodies, or a number of coal seams, at different depths. Levels are driven from the shaft at vertical intervals which may vary from 50 to 250 feet or more, and from these levels horizontal tunnels ('drifts') are driven either through the orebody, or through the coal seam, or parallel to the metalliferous veins. From the drifts, crosscuts are made into the orebody. When it is necessary to go vertically or steeply upwards in or near the orebody, a 'raise' is made; and if the required direction is downwards, a 'winze' is sunk. The material mined may be worked in 'stopes'.

In metalliferous mines the ore is drilled and blasted, the broken material falls to a lower level through ore passes ('chutes'), is drawn off from the orebins into cars, trammed to the hoisting shaft, raised to the surface, and transferred into large ore bins from which it is sent to the mill or concentrating plant for treatment. Several mines have reached a vertical depth below the surface of well over 8,000 feet. Among the deepest mines in the world are Robinson Deep and Crown mines in the Transvaal, S. Africa, St. John del Rey in Brazil, and Ooregum mine in the Kolar goldfield, India.

Flat-lying or low-dipping deposits are often worked by the pillar and stall method or on the longwall system. In the former, the extraction is from the stall, or room, while the pillars are left as supports for the roof. The pillars may later be replaced with cribbings of timber and waste material. In the longwall operations, a series of radial tunnels ('drives') are made from the shaft bottom towards the far end of the deposit. A peripheral drive is then made at the far end and the deposit is worked first in the parts remote from the shaft and the working face is gradually extended towards the shaft bottom. Roof supports are installed where the material is being excavated, and in the worked-out area the roof is allowed to subside. Mechanical cutters, scrapers for loading, conveyor belts, and other equipment mark the progress made in recent years in the mechanization of coalmining.

A common method of lode mining is to drive vertically or steeply upwards from the horizontal drives ('levels'), a series of ore passes ('chutes') at suitable intervals. The ore passes are then connected horizontally at a height of from 10 to 30 feet above the level to form the bottom of the stope for working the lode immediately above. The ore is then drilled and blasted, the broken material is passed through the chutes into bins, and loaded as required into trams. If the ground is firm enough, part of the broken ore is allowed to remain in the stope as a platform on which the miner stands to excavate the ore above. This method is known as 'shrinkage stoping'. It is not, however, employed where the walls of the vein are not strong enough to remain standing after the vein material has been removed; in such a case another method, known as 'square setting' is adopted. Square or rectangular sets of timber are erected between the walls of the vein and continued upwards as the ore is being excavated. Waste material is filled into the hollows between the timbers to strengthen the supports. A disadvantage of this method is the large amount of timber used, and where this is scarce or expensive, 'top slicing' may be more economical. In this method, the ore is worked downwards from the top of the deposit by slicing, the broken material is passed downwards through chutes, and the roof is kept in place by a mat of timber standing on supports.

We have considered some of the chief methods employed in lode mining but many important ore deposits are not in the form of veins or lodes, but occur as large irregular masses. One of several methods of working the latter is to drive a main haulage way below the bottom of the orebody, put up at suitable intervals a number of vertical holes to form ore passes, and work the deposit by 'caving'. The bottom of the ore is undercut and the overlying ground is allowed to subside and thus help in breaking the material. Once the subsidence starts, the caving usually continues so that where the conditions are suitable, this method provides a comparatively cheap form of mining. It is one of the chief methods used in working some of the famous low-grade 'porphyry copper ores' in the U.S.A.

Treatment of the Mined Material. The mined material in the form it reaches the surface is in most cases not in a condition for marketing. It has to undergo further treatment, usually in a milling or concentrating plant sited relatively near the shaft head to save transport of the waste material with which the required product is associated.

The milling process depends on the kind of desired mineral and the nature of the deposit. So numerous are the useful minerals and the kinds of deposits in which they occur, that we shall confine ourselves to a brief description of the milling ('dressing') of a few important minerals.

Except in the case of high-grade and valuable metalliferous ores which are usually sent direct to the smelters without further treatment on the mine, the excavated material is sent to the mill. The first essential in almost all milling operations is the preliminary crushing of the material and its further comminution by grinding to the required degree of fineness, depending on the nature of the material.

In many mineral deposits, the useful minerals are scattered through the rock and a great deal of waste material has to be discarded to effect concentration of the required product. Where barren, or almost barren pieces of rock can be readily recognized in the coarsely broken material, recourse is made to hand-sorting. The coarse material travels on a moving belt, or on sorting tables, and either the waste or the mineralized material (depending on their relative amounts) is picked off and dropped into conveniently placed receptacles. This is common practice for some non-metalliferous deposits, such as those containing asbestos, but may also be employed for certain types of ore.

Heavy minerals occurring in rocks are separated from the associated lighter minerals by gravity concentration in water after the material has been crushed. It is the oldest form of concentration and for minerals yielding tin, tungsten, gold, and some other metals it is the method still used to-day, but in a highly mechanized form. After crushing, the material is classified according to particle size and the classified 'heads' flow into compartments ('jigs') equipped with pulsating screens through which a column of water flows upwards. The heavy minerals settle to the bottom and are drawn off. Different size screens are used for the different classified material, and the 'middlings' (the material in which the useful and valueless have not been separated) are re-treated. For the more finely crushed or ground material, concentrating tables are employed. These are erected with a tilting surface, have parallel and sloping thin strips of wood ('riffles') on their surface, and are subjected to rapid pulsations which cause the water flowing over them to carry away the light substances over the lower ends of the tables, leaving the heavy minerals trapped on the riffles along the slope of which they gradually move sideways into receptacles.

Fine crushing and grinding are expensive operations, and a method which reduces to a minimum such procedure without loss of products has long been sought. Such a method has been devised recently but can be applied only to certain types of deposits, such as lead and zinc ores occurring in limestone, and a few others. Instead of water for gravity concentration, a heavy liquid is used in which the mineralized material will sink and the waste will float ('Sink and Float method'). Powdered galena, for example, mixed with water provides a medium in which limestone will float and the lead and zinc ore minerals will sink. Finely ground barytes is similarly used for some sink and float processes.

The most spectacular advances hitherto made in the concentration of metalliferous minerals result from the adoption of the 'flotation process'. During the last two or three decades most of the lead, zinc, copper, and other base metal ores have been treated by this process, which has made it possible to work enormous tonnages of low-grade mineralized deposits which could not previously be treated economically. The finely ground ore in the wet state is first classified on grain size, a small quantity of oil or chemicals is added, and the liquid flows into flotation cells. Air is pumped into the cells to form a froth of air bubbles coated with the chemical used. The metallic particles cling to the bubbles and are carried upwards to form a scum which is swept into collecting troughs. The concentrates are then dewatered and are ready for smelting.

Minerals which are strongly or weakly magnetic can be separated from the non-magnetic material magnetically. The iron mineral, magnetite, which is strongly magnetic, can be separated from the gangue by passing the material on a belt over a magnetized pulley. The gangue is carried forward on the belt while the magnetite is attracted and drops into a receptacle near the pulley. The tungsten mineral, wolfram, is weakly magnetic and occurs frequently in association with the tin mineral, cassiterite, and other non-magnetic minerals. The wolfram is separated from the mixed concentrates by passing them over an electromagnetic separator.

Asbestos fibres, when freed from the enclosing rock material by crushing and disintegration, are concentrated in strong artificially produced air currents which blow the fibres away from the waste material.

Native gold occurring in a quartz vein is a free-milling ore and much of the gold can be recovered by amalgamation with mercury. The crushed ore is ground finely in water in ball mills, rod mills, or with stamp batteries, to release the gold particles. The ground material ('pulp') is then passed over metal plates coated with mercury ('amalgamating plates') and the gold is taken up by the mercury ('quicksilver') to form an amalgam. This is scraped off the plates, the mercury is driven off by retorting and is recovered for further use, and the gold remains in the retort. A modification of this method is to introduce the mercury during the grinding process, or to rotate the pulp in amalgam barrels instead of passing it over the plates.

Extraction of gold from certain complex ores by amalgamation is not practical and recourse is made to cyanidation, a process that can be used only for gold and silver ores, but not for auriferous ores containing much copper and certain other metallic minerals. For the cyanide process, the ore is ground finely in water, is then de-watered and transferred into large tanks through which passes a solution of potassium cyanide for dissolving the gold. The gold solution is passed through a filter where zinc is used for precipitating the gold which is then purified and cast into rectangular bullion bricks. Some gold ores containing sulphides are first roasted to drive off the sulphur before they undergo cyanidation.

Leaching Processes. Minerals which are soluble in water like the nitrates and chlorides of sodium and potassium, and some copper minerals which are readily soluble in acids, are subjected to a leaching process.

Certain natural salts are dissolved in water and treated in large tanks for fractional precipitation at different temperatures. Thus Chilean nitrate may be freed from the waste material with which it is associated by simple extraction with water.

The chief reagent used for leaching cupriferous ores is the sulphuric acid which is formed naturally as one of the decomposition products of the unstable sulphide of iron, pyrite or iron pyrites. At the famous Rio Tinto mines in Spain, the cupriferous pyritic ore is stacked in heaps containing millions of tons of ore and allowed to weather in the open. The acid resulting from the decomposition of the pyrite and of some of the copper sulphides, dissolves much of the copper which is then precipitated by passing the solution over scrap iron, upon which the copper is deposited and later recovered.

Smelting. Smelting is the process by which the metals are extracted from metalliferous minerals by melting them in blast, reverbatory, or other furnaces. Before smelting, the minerals have usually been freed of waste material by concentrating them in the milling plant.

The fuel most commonly used is metallurgical coke, or anthracite. A fluxing material is mixed with the concentrates to form the charge. The flux facilitates melting, forms a slag of the waste which rises to the top of the molten mass, and enables the metal to sink to the bottom, where it can periodically be tapped and run into moulds.

Minerals containing sulphur and arsenic are roasted before they are smelted to drive off those elements. If much arsenic is present, precautions are taken to sublime the arsenic as an oxide to prevent poisoning the air of the neighbourhood. Sulphide copper ores, after roasting, are smelted and the metal is drawn off as a copper *matte*. This is then treated in converters, where air is blown through the melt to get rid of more impurities and to form *blister* copper, which is later refined.

Lead concentrates are roasted and smelted whereas, from zinc concentrates, the zinc, being volatile, is distilled in retort furnaces. In some large mines, the lead and zinc are recovered electrolytically. Mercury ores are heated in furnaces and the volatile metal is condensed in retorts.

Refining. The metal extracted after smelting frequently contains impurities which have to be removed by refining processes before the metal is marketable; and precious metals like gold and silver may be present in the smelted products of copper, lead, and zinc and form valuable by-products.

Two of the chief methods of purifying metals are fire refining and electrolytic refining. Lead is fire-refined to yield the silver it so frequently contains, and non-auriferous copper matte is converted into high grade blister copper. The blister from the smelters is cast in anodes and these are placed in tanks containing an acid electrolyte through which a current is passed. Copper from the anode is dissolved and deposited on the cathode as pure metal known as 'electrolytic copper'. The sludge formed during this electrolysis contains the impurities and any gold and silver which was present in the blister. A small percentage of the world's gold is thus recovered from copper ores.

CHAPTER XII

MINERALS IN THE INDUSTRIAL AGE

Since the eighteenth century, when Abraham Darby, a Shropshire Quaker, first used coke for smelting iron, and James Watt invented the steam engine, coal has been the main source of energy, and iron the backbone of industrial civilization. The industrial revolution made coal and iron the most coveted and valuable mineral resources of a country, and the rise of industrial nations has been largely dependent upon their possession of adequate quantities of these two essential materials. Moreover, the geographical distribution of coal and iron has been the main factor in controlling the location of the great manufacturing centres, towards which so much of the world's trade is attracted.

A hundred years ago the annual world production of pig *iron* was not more than five million tons, and the only forms of the metal used for constructional purposes were cast iron and wrought iron. In 1856, however, Henry Bessemer announced his process of rapidly converting crude pig iron into steel on a large scale and at low cost, thereby ushering in the steel age. At present steels are by far the most important ferrous metals, being followed in turn by cast iron and wrought iron. The world output of pig iron now exceeds 100 million tons a year, and that of steel ingots and castings amounts to about 150 million tons. Modern civilization has no adequate substitute for iron and steel, the consumption of which is more than ten times as great as that of all other metals combined. It is beyond the compass of this book to recount the multifarious uses of iron and steel in the construction of railways, tramways, ships, buildings, and innumerable machines.

Although the list of iron-bearing minerals is a lengthy one, four minerals only are important sources of the metal. These are, in order of importance: hematite, Fe_2O_3, a red oxide with 70 per cent iron; limonite, $Fe_2O_3 . nH_2O$, a yellowish-brown mineral containing about 60 per cent iron; magnetite, Fe_3O_4, a black highly magnetic oxide, with theoretically 72 per cent iron; and siderite, $FeCO_3$, or spathic iron ore, with 48 per cent iron.

With the advent of the industrial age about a century ago mineral production received its first real impetus. The rapid development in the use of iron and steel throughout the civilized world was accompanied by an ever-growing demand for other metals, such as copper, lead, zinc, and tin. During much of the nineteenth century the United Kingdom was a foremost producer of these metals, supplying about half the world's need of iron, copper, lead, and tin. The introduction of manganese steel and ferro-alloys towards the close of the century revolutionized engineering and metallurgical practice, and heralded the age of special alloys. It was discovered that by adding to steel small quantities of previously little-used elements, particularly chromium, nickel, and tungsten, the metal became endowed with special properties, such as increased hardness, tensile strength, and resistance to abrasion, corrosion, and fatigue. These alloying elements soon became key metals—as essential to the steel industry as yeast is to bread-making—and they quickly attained an importance out of all proportion to the amounts consumed. Their geographical distribution as sources of supply acquired international significance.

The great technical progress achieved during the past sixty years in the engineering and allied industries can be attributed largely to the increasing employment of alloy steels. Their use has led to much greater efficiency in all types of engines, cutting tools, armaments, constructional girders, and so forth, besides prolonging the life of machinery, reducing breakdowns, and promoting safety. Only brief reference can be made here to some of the outstanding functions of the various ferro-alloy elements, and the minerals from which the alloying metals are obtained.

Manganese, which is principally derived from the two black oxide minerals, psilomelane and pyrolusite, is essential in the manufacture of all steel because of its potent cleansing or deoxidizing effect during the smelting process. On an average about 14 lb. of manganese is thus used for every ton of steel produced. In addition to its purifying action, the incorporation of manganese endows steel with supplementary virtues, notably increased hardness and toughness. Indeed, the discovery of manganese steel by Sir Robert Hadfield of Sheffield in 1882 was a landmark in the development of alloy steels. On account of its prolonged resistance to abrasion a steel of this kind, containing about 12 per cent manganese is especially suitable for rock-crushing and digging machinery, curved rails and cross-overs.

Chromium, one of the most indispensable of the ferro-alloy metals, is obtained solely from the mineral chromite, theoretically $FeO.Cr_2O_3$. The addition of even small amounts of chromium imparts to steel increased hardness, toughness, and resistance to chemical attack, besides permitting reduction in weight of metal without sacrifice of strength, in automobiles, railway carriages, and aeroplanes. The stainless steels, first produced in 1913 by Brearley of Sheffield, contain about 14 per cent chromium, but the popular super-stainless corrosion- and heat-resisting varieties now used for cutlery and domestic utensils include about 18 per cent chromium and 8 per cent nickel. Alloy steels with still higher chromium and nickel contents find extensive service in chemical and surgical equipment and in the resistance elements of electrical heaters.

Nickel ranks second in importance to manganese among the ferro-alloy metals. It is extracted chiefly from the mineral pentlandite (Fe,Ni)S, which usually occurs in intimate association with the iron sulphide, pyrrhotite, as in the famous nickel deposits of Sudbury, Ontario. Garnierite, a hydrous nickel-magnesium silicate found in certain weathered serpentines, notably in the French colony of New Caledonia, is a minor source of the metal. Nickel alloys are among the best known for machine parts subjected to heavy loads, shock, abrasion, corrosion, and temperature changes. Since Riley, of Glasgow, demonstrated nearly sixty years ago the superiority of nickel steel over ordinary carbon steel for armour plate, low-nickel steels with less than 7 per cent nickel have been widely used for the moving parts of innumerable machines, and for architectural and bridge construction. The high-nickel steels, with 7 to 35 per cent nickel, include heat-resistant and corrosion-resistant stainless steels employed in chemical apparatus, furnace parts, marine fittings, and cooking utensils. An alloy known as 'Invar', composed of iron with 36 per cent nickel, is practically unaffected by temperature changes and is therefore in demand for making accurate measuring tapes, pendulums, and precision instruments.

Tungsten, prominent as a constituent of 'high-speed steels' used for cutting metals, is obtained mainly from the two minerals, wolframite, $(Fe,Mn)WO_4$, and scheelite, $CaWO_4$. Tungsten steels retain their hardness and excellent cutting properties at red heat and are self-tempering. It is thus not surprising that their introduction little more than forty years ago revolutionized metal-cutting practice. High-speed steel tools containing about 18 per cent tungsten with some chromium and vanadium can be operated twenty times faster than those made of plain carbon steel, and they are also capable of much deeper cuts. These valuable steels are now in demand for valves and valve seats, chisels, stamps, armour plate, and heavy ordnance. A recent development is the use of tungsten in the fabrication of tungsten carbide as a super-hard cutting tool or facing for machine work, and for making wire-drawing dies much superior to the best steel dies. The powdered carbide, bonded with a small amount of cobalt, is a more effective cutting agent than even high-speed tungsten steel and is second only to the diamond in this respect. Because of its electrical resistance and high melting point metallic tungsten has no rival as a filament for electric light bulbs. It is doubtful whether any other metal, used in equal amount, has been of greater boon to mankind during the past thirty years, an annual consumption of only 100 tons of tungsten being sufficient to provide enough filament for more than 1,000 million electric lamps each year.

Molybdenum, commonly called 'Molly', is obtained almost entirely from the soft, lustrous black sulphide, molybdenite, MoS_2. Its most important function is as a strengthening alloy in cast iron and steel, often in conjunction with chromium and nickel. Molybdenum is claimed to have twice the hardening power of tungsten, and since it retains temper even at red heat it serves as an admirable substitute for tungsten in high-speed tools. Steels with less than one per cent molybdenum are required in the automobile and railroad industries, and for making agricultural implements, whilst high-molybdenum steels are favoured for permanent magnets, dies, rustless steels, and high-speed tools. Less than one per cent of *vanadium* suffices to impart beneficial effects to steel, rendering it resistant to fatigue, shock, and twisting stress and thus well adapted for service in axles, shafting, springs, and other parts involved in strain. Moreover, when used in combination with molybdenum, vanadium endows steel with the valuable characteristics of high-speed tungsten steel. The chief economic minerals from which vanadium is extracted are the sulphide, patronite; the yellow vanadate, carnotite; the chlorovanadate, vanadinite; the mica, roscoelite; and the complex lead vanadate, descloizite. Considerable quantities of the metal are also obtained from the treatment of soot collected from ships burning Mexican and Venezuelan oil.

The minor ferro-alloy metals include *cobalt*, which is recovered principally as a by-product of Central African copper ores containing the sulphide mineral, linnaeite (Co_3S_4), and black oxides of cobalt. Formerly most of the metal was obtained from smaltite ($CoAs_2$) and cobaltite (CoAsS). Metallic cobalt is utilized mainly in 'stellite', an alloy of cobalt, chromium, and tungsten or molybdenum, which is capable of machining hard metals rapidly even at high temperature. Corrosion-resisting steels suitable for razor-blades and surgical instruments commonly contain cobalt, and among the most powerful permanent magnets are those made of cobalt-rich steel, which are capable of lifting more than sixty times their own weight. *Titanium*, won from the minerals ilmenite ($FeTiO_3$) and rutile (TiO_2), is employed to a limited extent for removing oxygen and nitrogen from steel, and as an alloying agent to increase the tensile strength of chrome steel. Within recent years *silicon* steels, endowed with improved elasticity, have been used for car springs and bridgework, and on account of their high resistance and magnetic permeability they find specialized service in electrical machinery.

Zirconium, derived from the two minerals, zircon ($ZrSiO_4$) and baddeleyite (ZrO_2), is a comparative late-comer to the steel industry, where it is sometimes used in making armour plate, projectiles, and high-speed cutting tools. Much of the steel employed in the manufacture of tanks and other armaments in Australia during the past few years had to be hardened by small additions of zirconium extracted from the zircon-bearing sands of New South Wales, because the continent was then cut off from supplies of the commoner hardening metals.

Copper, the first utilitarian metal of antiquity, still ranks as the most important of the non-ferrous metals and is second only to iron as a metal essential to industrial civilization. It is extracted chiefly from the sulphide minerals chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), and bornite (Cu_5FeS_4), and from various green carbonates and sulphates of copper. Within recent years the annual world production of newly mined copper has exceeded two million tons. The rapid growth of copper production during the past fifty years is intimately related to the expansion of electric power generation. Copper is the handmaiden of electricity, more than half the output of the metal being consumed in the 'pure' form in the production, transmission, and utilization of electricity. In the realm of non-ferrous alloys copper is the base of a greater range of different alloys than all other metals combined. Two of the best known copper alloys are the brasses, composed of copper and zinc, and the bronzes, consisting essentially of copper and tin although zinc and several other metals may also be present as minor constituents. The familiar penny is a 'bronze' containing 97 per cent copper, 2·5 per cent zinc, and 0·5 per cent tin. Among the scores of other copper-bearing alloys are Monel metal, a corrosion-resisting nickel-copper alloy used for turbine blades, pump bodies, and kitchen ware; and nickel-silver, formerly called 'German silver', with 65 per cent copper, together with zinc and nickel in equal parts, used as a popular basis for plated silver tableware.

Lead and *zinc* probably rank next to copper as essential non-ferrous metals in modern industry. The great increase in the consumption of lead during the present century has been due largely to the heavy demand for the 'base' metal for making storage battery plates, as a covering for electric cables, and for the manufacture of 'white lead' and 'red lead' pigments. Most of the metal is recovered from the simple sulphide mineral, galena, PbS. A hundred years ago zinc metal had very few uses beyond contributing to the small output of brass. Nowadays, the process of coating thin steel sheets and wire with metallic zinc to prevent rusting, known as galvanizing, accounts for about half the world's consumption of zinc. The remainder is principally used in the manufacture of brass and in the rapidly expanding pressure die-casting industry for making automobile carburettors, petrol pumps, hub caps, and radiator grilles. Zinc is obtained mainly from the mineral sphalerite, or zinc blende (ZnS), though the carbonate, smithsonite, and the hydrous silicate, hemimorphite, are minor sources of the metal.

Although *tin* was certainly one of the first metals employed by man, it was not until the nineteenth century that it was used in industry on a large scale. In 1800 the annual world production of the metal was less than 9,000 tons, whereas in 1940 it had reached nearly 250,000 tons, practically the whole output being obtained from the oxide mineral, cassiterite (SnO_2). During ancient and medieval times tin was used mainly for making bronze weapons, implements and ornaments, and pewter utensils. At present, by far the greatest single use of the metal is for making the lowly 'tin' can, consisting of thin sheet steel coated with a veneer of pure tin. Within the past twenty years there has been a spectacular increase in the employment of tin cans for food storage, nearly 400 million being made in Great Britain alone in 1939. Actually only about one per cent of the weight of an empty can consists of tin metal, one pound of which is normally sufficient to cover more than 200 square feet of tinplate. Terne plate, made by applying a coating of tin and lead instead of pure tin, is utilized largely for roofing and for making petrol tanks for automobiles. Nearly a quarter of the present production of tin is allocated to the manufacture of tinsmiths' and plumbers' solders, which are alloys of tin and lead used chiefly in soldering tin cans, automobile radiators, and electrical equipment. 'Babbit' or bearing metal, containing about 90 per cent tin, 7 per cent antimony, and 3 per cent copper is widely employed for bearings in aircraft, locomotives and machines, and approximately 7 per cent of the world's tin output finds its way into various types of bronzes.

Half a century ago metallic *aluminium* was regarded as an expensive scientific curiosity although, next to oxygen and silicon, it is the third most abundant element in the earth's crust. In 1937 nearly half a million tons of the metal were produced, the world output rising to the million mark in 1941 and soaring to nearly two million tons in 1943. By far the most important source of the metal is the rock bauxite, a fine-grained mixture of hydrous aluminium oxide minerals including gibbsite, $Al(OH)_3$, and diaspore, $AlO(OH)$, usually contaminated with iron. Lightness, strength, electrical conductivity, and resistance to corrosion account for the great popularity of aluminium in modern industry. Before the recent world war the metal was being widely used in aeroplane construction, streamlined trains, automobiles, cooking utensils, and household appliances, and a surprising amount was consumed instead of copper in electrical power transmission lines. The phenomenal increase in the production of aluminium during the past few years has been due principally to the insatiable demand for more aircraft, in which the metal is used both in the pure form and in light alloys of high tensile strength, such as duralumin (96 per cent aluminium, 3 per cent copper, together with magnesium and manganese).

The expansion in the demand for *magnesium* metal and its 'ultra-light' alloys in recent years is without parallel in the history of the use of metals. Thirty years ago magnesium, one of the lightest of metals, was used mainly as photographic flashlight powder, and in 1925 the total world production of the metal was only 1,800 tons. By the end of 1941 the annual output had reached 100,000 tons, and in 1943 it amounted to 252,000 tons. Until about ten years ago most of the world's supply of magnesium metal was produced in Germany, where it was obtained by the electrolysis of molten magnesium chloride derived from the famous salt deposits of Stassfurt. Natural brines from deep saline wells have provided considerable quantities of magnesium in the United States, and the metal is now being extracted from sea-water on a large scale in Great Britain and elsewhere. Since a cubic mile of ordinary sea-water contains more than five million tons of magnesium, the potential reserves of the metal are virtually illimitable. Other sources of magnesium include the minerals magnesite ($MgCO_3$) and dolomite ($CaMg(CO_3)_2$), which are also widely employed for making refractory bricks for lining steel furnaces and basic converters. Magnesium metal is used chiefly in light alloys in aircraft and automobile construction, for crank-cases, engine parts, frames, and so forth; it also serves as castings for optical instruments, cameras, vacuum cleaners, portable typewriters, and artificial limbs. Much of the recent war demand for the metal was required for making incendiary-bomb casings and flares. Metallic magnesium is now finding increased service in the metallurgical industry as a deoxidizing and desulphurizing agent in the manufacture of nickel, Monel metal, brass, and bronze. Aluminium is the most important alloying addition to magnesium, though manganese is almost always incorporated in small amounts, and zinc is often added. Such alloys possess the great advantage of lightness, strength, and ready machinability.

From this incomplete review of the more important metals of the industrial age we pass to a brief consideration of some of the minor metals and minerals which are comparatively new to industry and in many cases have leapt from obscurity into prominence within the past two decades. For convenience we shall deal with these mineral raw materials in alphabetical order.

Andalusite, an aluminium silicate (Al_2SiO_5), was first mined about twenty-five years ago in the United States for use in the manufacture of ceramic sparking-plug cores, chemical and insulating porcelain, and special refractory bricks employed in electric furnaces and cement kilns. Recently the mineral has been worked in Scandinavia as a source of metallic aluminium.

Apatite, a calcium phosphate mineral, is widely distributed in nature but is mined on a large scale only in the unique deposits of the Kola Peninsula in Northern Russia, discovered in 1926. These immense deposits now yield more than two million tons of apatite annually for the preparation of superphosphate fertilizers.

Bentonite, a variety of clay which either swells enormously in water or has strong absorptive properties, is unrivalled as a bleaching agent and as a filter in oil refining. It is also in growing demand for reconditioning moulding sands, for rotary well-drilling muds, and a host of other uses. From a negligible quantity twenty years ago production in the United States alone now exceeds 250,000 tons a year. A similar amount of fuller's earth, analogous to certain bentonites, is being exploited for petroleum refining and the clarification of vegetable oils and animal fats.

The mineral *beryl*, a beryllium silicate, is practically the only commercial source of the infant metal beryllium, which, when added to copper or aluminium in small amounts endows those metals with greatly increased tensile strength, corrosion- and fatigue-resistance. Vibrator springs made of copper-base beryllium alloys are reputed to show no deterioration even after being stressed hundreds of millions of times. Such endurance has won for beryllium the epithet of the 'tireless metal'. The alloy is also used in many types of instrument springs, valves, switches, and carburettors, and because of its non-sparking properties it is valued in explosive factories and oil refineries. Beryllium can be employed as a source of neutrons for the bombardment and splitting of uranium atoms, and for slowing down the high-speed fission neutrons emitted from uranium in order to control the chain-reaction involved in the explosion of an atomic bomb.

Borax, a hydrous sodium borate found mainly in the desert regions of California, is not only a well-known household commodity but also serves in a surprisingly wide range of industries. Production of this important mineral has more than trebled since 1920, owing chiefly to its growing use in the manufacture of heat-resisting glass of the Pyrex type, enamelware, glazes, and fluxes for welding metals. *Brucite*, magnesium hydroxide, $Mg(OH)_2$, now being mined in Canada and the United States as a source of metallic magnesium and for the manufacture of furnace refractories, has been of commercial importance for little more than ten years.

Cadmium is a newcomer among metals. Its production has multiplied rapidly during the past twenty years, mainly for use as a rustless coating on iron, as a cadmium-copper alloy for trolley wires and long cable spans, and as an alloy with nickel, or silver and copper, in high pressure anti-friction bearings in automobiles. Much of the cadmium of commerce is derived from the somewhat rare sulphide mineral greenockite, CdS, the metal being obtained entirely as a by-product chiefly from the smelting and refining of zinc ores containing cadmium-bearing blende and greenockite. *Caesium* is extracted mainly from the rare mineral pollucite, which is mined in South Dakota. Although its industrial consumption is small, this light-sensitive metal has important applications in the photoelectric cell, the retina of the 'electric eye', used extensively in talking pictures, television, traffic controls, alarms, and similar apparatus. It also serves as a 'go-getter' in removing the last traces of air in radio valves. Although *calcium* is one of the most abundant elements in nature its use in metallic form as a scavenger or deoxidizer in the refining of copper, nickel, and other non-ferrous metals is only of recent practice. It is also in current demand as a hardener of lead-base alloys, since the addition of as little as 0·04 per cent of calcium metal nearly trebles the strength of lead besides producing an age-hardening effect. *Cerium* is extracted together with other rare-earth elements from the mineral monazite, a constituent of certain beach sands. When alloyed with 30 per cent of iron the cerium metals form a 'pyrophoric' alloy now extensively used as 'flints' or sparkers for cigarette lighters, carbide lamps, &c. Cerium is also gaining favour for use in arc-lamp electrodes, glassware, photography, and, because of its great affinity of oxygen, as a metal scavenger. The oxide, ceria, is still used in conjunction with thorium in the manufacture of incandescent gas mantles.

In recent years there has been a remarkable increase in the use of *diamonds* for industrial purposes. More than two-thirds of the annual diamond production of about ten million carats is now used for diamond drilling, diamond-set machine tools, diamond dies for wire drawing, and in crushed form for bonded abrasive wheels and saws. The Brazilian black diamond, carbonado, and especially the dark-coloured or flawed diamond known as bort, are the two chief types of abrasive diamond, most of the production coming from alluvial stream and beach deposits in Africa, particularly those of the Belgian Congo.

Felspar, the commonest of all rock-forming minerals, has long been used in ceramics for manufacturing pottery, tiles, and glazed wares, and also for making enamels, but during the past decade or so more than half the world's yearly production of 500,000 tons has been utilized in the glass industry to contribute alumina to the glass batch.

Less than twenty years ago the annual world output of *indium* was a fraction of an ounce. The metal, which is derived chiefly from zinc-refinery residues, is now coming into wide use as a protective surfacing for bearings in internal combustion engines, as a corrosion-resistant dental alloy, and as a non-tarnishing plating for silverware.

In 1926 a new sodium borate mineral, *kernite,* was discovered in association with borax in the Mohave Desert of California. It is now the chief source of the world's refined borax, more than 90 per cent of which comes from the western United States. *Kyanite,* an aluminium silicate mineral, Al_2SiO_5 has gained considerable favour since 1920 as a material for making high-grade porcelain for sparking-plugs, refractory bricks, and for toughening glass.

Lithium, the lightest of metals, obtained chiefly from lepidolite mica and the silicate mineral spodumene, is now finding service as a hardener in various light alloys and bearing metals. Owing to its hygroscopic property lithium chloride is in growing demand for air-conditioning and industrial drying. In addition to the continued use of lithium compounds in pharmaceutics, the mineral lepidolite is being employed to an increasing extent in the manufacture of glass and enamels.

Monazite, already mentioned as the source of cerium, also contributes most of the world's thorium, still widely used for making incandescent gas mantles and for reducing the brittleness of electric light filaments. Thorium is one of the key elements which possess characteristics essential for atomic bombs and is a potential source of atomic energy, for it is fissionable and has an isotope capable of violent explosive chain reaction. The world's annual consumption of monazite before the recent war was about 5,000 tons, the mineral itself containing from 2 to 10 per cent of thoria (ThO_2). Thorium dioxide is a super-refractory used in crucibles for melting pure metals at temperatures up to 2,300°C. The mesothorium which always accompanies thorium in monazite is much more radioactive than radium and is highly valued in the treatment of cancers and malignant skin diseases, and as a constituent of luminous paints.

Nepheline, essentially a sodium aluminium silicate, has within the past decade rivalled felspar as a source of alumina in the glass and ceramic industries. In the Kola Peninsula of Northern Russia nepheline is being mined on a large scale as a substitute for bauxite in the manufacture of metallic aluminium. *Niobium*, called columbium in the United States, is obtained mainly from the mineral columbite, $(Fe,Mn)Cb_2O_6$. It was practically useless twenty years ago but is now employed to improve the welding properties of stainless chromium steels and high-speed tool steels. Because of its great affinity for gases the metal is a valuable 'getter' or absorber of the last traces of gas in radio valves and vacuum tubes. Most of the supply is derived from the columbite deposits of Nigeria, the recent annual production being about 500 tons.

Production of the *platinum* metals has increased enormously during the present century, and now exceeds 600,000 ounces a year. Apart from their popular use in jewellery platinum and palladium have wide application in dentistry, as catalysts in the manufacture of sulphuric acid, in electrical apparatus for contact-points, in thermocouples, laboratory equipment, and as linings for processing and reaction vessels. Osmiridium is well known in the form of tips of fountain-pen nibs, and rhodium is rapidly gaining favour as an untarnishable film on silver articles. Most of the world's platinum metals are recovered as by-products of the refining of nickel-copper ores at Sudbury, Ontario, and from the river alluvial deposits of the Ural Mountains.

We have already mentioned the remarkable development in the use of piezoelectric *quartz crystals* (page 83) for radio-frequency control and long-distance telephone communication. Owing to heavy war demands Brazil, practically the only source of suitable crystals, has recently been exporting many thousands of tons of piezoelectric quartz, whereas the annual world output in 1910 amounted to only about 20 tons.

Radium, a disintegration product of uranium minerals, is chiefly employed in curative medicine, especially in the treatment of cancer and skin diseases. Luminous paints for dials, signs, gun-sights, and so forth consume about 10 per cent of the total annual production of about 200 gm., and small amounts are used for detecting inner flaws in metal castings and forgings. Canada and the Belgian Congo are virtually the only important producers of radium.

Selenium, a by-product obtained from the electrolytic refining of copper ores, is being used in rapidly increasing quantities, largely for decolourizing green glass and as a colour pigment in ruby signal glass. Since the electrical conductivity of selenium is proportional to the intensity of light falling upon it, the metal is employed in photoelectric cells in cinema 'talkie' mechanism, television apparatus, automatic street lighting, burglar alarms, and other ingenious devices. The average annual output of selenium is little more than 300 tons, and is derived almost wholly from the treatment of copper ores in the United States and Canada. Although *silicon* is second only to oxygen as the commonest element in the earth's crust, the metal is among the newcomers to industry. Increasing amounts of it are being used as deoxidizing and heating agents in making steel and ferro-alloys, and the addition of about one per cent of silicon confers improved elasticity to steels suitable for car springs and bridgework. Large quantities of silicon, extracted from quartz, have recently been incorporated in a valuable series of aluminium alloys, the most useful one containing about 12 per cent silicon. These alloys, which possess high strength, ductility, and excellent castability, are now in considerable demand for diesel engine mountings and for gearbox cases and crank-cases in other internal combustion engines. *Sodium,* another common element, has only been produced as a metal on a commercial scale within quite recent times. It is extracted from the well-known mineral rock salt, or halite, $NaCl$. The annual output of the metal now exceeds 250,000 tons, most of which is used in making tetraethyl lead for anti-knock petrol, and in the manufacture of synthetic indigo and sodium cyanamide. Small amounts of the metal are employed for improving the internal structure of the new aluminium-silicon alloys, thereby endowing them with much greater hardness and toughness.

Tantalum was first used commercially in making filaments for incandescent electric lamps, but was superseded for this purpose in 1911 by tungsten. Owing to its remarkable resistance to acid corrosion, tantalum is highly valued in acid-resistant apparatus, surgical and dental instruments, and by the medical profession for pins, plates, and screws in bone fixation. The great capacity of the metal for absorbing gases makes it valuable in the construction of vacuum tubes, and it is also utilized in the plates and grids of radio valves. Since tantalum carbide is almost as hard as diamond it serves admirably for super-hard tipped tools, and because the metal allows electric currents to flow in one direction only it acts as an automatic rectifier of alternating current. Practically the only source of tantalum is the mineral tantalite, $(Fe,Mn)Ta_2O_6$, which is mined principally in Western Australia, the Belgian Congo, and Brazil. *Tellurium* metal is obtained wholly from the slimes formed during the electrolytic refining of copper ores containing traces of tellurium. Twelve years ago the total annual production of the metal was about one ton, since when it has risen to nearly 50 tons, of which Canada and the United States contribute almost equal amounts. It is used in the manufacture of hard tough rubber for hose and cable coverings, and the addition of less than one tenth of one per cent tellurium endows lead with increased hardness, strength, and resistance to corrosion and wear. Small quantities of tellurium are employed in producing blue and brown tints in glass and porcelain, in corrosion-resistant coatings on certain metals, and in some aluminium and steel alloys.

Titanium has recently become an important industrial substance largely because its oxide yields a white paint pigment of extraordinary wearing power, much superior to lithopone, white lead, and zinc oxide. Other uses of the oxide are in the manufacture of lacquer enamels, porcelain, artificial teeth, glass, rayon, rubber, and paper, whilst the tetrachloride serves to produce smoke-screens and sky writing. The metal has a limited use in removing oxygen and nitrogen from steel, and as an alloying ingredient in high-speed steels, chromium steels, and some complex aluminium alloys. Kenmetal, a tungsten-titanium carbide of great hardness, is used in cutting tools, valve seats, and wherever resistance to wear is essential. Ilmenite, $FeTiO_3$, and to a smaller extent rutile, TiO_2, are practically the only commercial sources of titanium. Curiously enough the former, although a dense black mineral, is used for making white pigments, whereas rutile is mainly employed in electric welding-rod coatings to stabilize the arc. The annual production of ilmenite, largely derived from the beach sands of

Travancore in Southern India, and the titaniferous ores of the Adirondacks, now exceeds half a million tons, whilst the output of rutile is approximately 2,500 tons.

Until a few years ago *uranium* ore was mined not so much for the metal itself as for its radium content, though salts of uranium have long been used for making iridescent glass, for imparting yellow and brown tints to glass, porcelain, and pottery, as mordants in dyeing and calico-printing, and in photography. On an average 750 tons of uranium ore are needed to produce about 5 tons of uranium salts and 1 gm. of a radium salt, and 11,000 tons of ore containing 1 per cent U_3O_8 would yield one ounce of radium. With the explosion of the atomic bomb on Hiroshima in 1944 the public became aware of the startling amount of energy pent up inside the uranium atom, and there can be no doubt that the principal use of the element in the future will be in the realms of atomic energy. About 0·7 per cent of uranium consists of the isotope U-235, one pound of which is said to contain latent energy equivalent to the power developed in burning nearly 2,500 tons of coal or 1,500 tons of petrol. To release this latent energy the isotope 235 must be concentrated from its parent source and bombarded with neutrons so as to provide the explosive atom U-236, which violently releases its energy when brought into contact with a source of hydrogen. The principal ore mineral of uranium is uraninite or pitchblende, approximately UO_2; its brightly coloured oxidation products contribute subordinate amounts of the metal, as does the yellow hydrous vanadate, carnotite, found disseminated in sandstones in Colorado. At present, the pitchblende deposits of the Great Bear Lake in Canada, discovered in 1930, and those of the Belgian Congo, opened up in 1923, yield nearly all the world output of uranium.

Vermiculite, an alteration product of biotite and phlogopite micas, expands on heating to as much as sixteen times its original volume. Little more than a mineralogical curiosity twenty-five years ago, it now claims increasing attention as a heat and sound insulator when used in a loose form or mixed with Portland cement, concrete, and plasters in various moulded slabs, flexible sheets, and plastic masses. Most of the world's production, now amounting to more than 50,000 tons a year, comes from Montana and South Africa.

We have outlined the function of certain iron and ferro-alloy minerals during the industrial age, and indicated the role of some of the many minerals that have attained commercial importance within the past two or three decades. New methods of utilizing minerals are constantly being discovered, and as a result of intensive research during the recent world war the industrial demand for many minerals is sure to be on a greatly increased scale.

CHAPTER XIII

SOME INTERNATIONAL ASPECTS OF MINERAL RESOURCES

No SINGLE nation or empire possesses adequate supplies of all the minerals necessary for its industrial and agricultural needs. This is not surprising when it is realized that certain essential minerals are remarkably restricted in their distribution, and that less than one per cent of the earth's land surface covers mineral deposits of economic importance. The volume and variety of mineral raw materials required for maintaining the industrial status of a country are so great that national self-sufficiency in minerals cannot be attained even under the exigencies of war. Moreover, as 'new', comparatively rare minerals enter the expanding field of industry, nations become ever more interdependent for their mineral supplies.

Many countries are devoid of most of the minerals they require, and even the three great political units, the British Empire, the United States, and the Soviet Union must each rely upon outside sources for some essential minerals. In the case of certain minerals the world has recently been largely dependent upon restricted areas for its supplies, such as nickel from Sudbury in Ontario, molybdenum from Climax in Colorado, borates from the deserts of California, piezoelectric quartz from Brazil, and uranium from the Great Bear Lake in Canada and from Chinkolobwe in the Belgian Congo. Freedom of access to mineral supplies and their uninterrupted international flow are thus necessary for the economic prosperity of industrial nations, and the imposition of barriers to world trade in minerals contributes to international disharmony.

The desire to acquire extra mineral wealth has long been an urge to imperialism, and on many occasions throughout history powerful nations have resorted to conquest largely in order to gain valuable mineral deposits. In our own time the acquisitiveness of the German and Japanese rulers was aggravated by their eagerness to possess essential mineral raw materials deficient in their own countries, and this craving undoubtedly helped to precipitate world conflict. Competition among the leading industrial nations for the political and commercial control of mineral deposits will probably continue until these resources, regardless of their location, come to be regarded as the heritage of all peoples, to be exploited for the common good.

No country can wage protracted war without amassing or having access to the mineral raw materials necessary for the manufacture of modern armaments. Mineral supplies have thus profoundly affected the course of conflict between nations, and international supervision of their allocation in recent years might have served to control or even prevent war. With the advent of the atomic bomb the allied nations have been quick to realize the necessity of controlling the production and distribution of uranium and thorium ores.

Great Britain is now so deficient in the majority of industrial minerals that it seems difficult to believe that during the nineteenth century she was successively the world's largest producer of lead, copper, tin, iron, and coal. Her great industrial strength was built chiefly on her resources of coal and iron, and on cheap transportation to the world markets. With the introduction, during the last quarter of the nineteenth century, of manganese steel and other ferro-alloys endowed with special properties, Britain's economic independence waned, for the vital constituents of the improved steels had to be imported from overseas. At the same time, increased costs of deeper mining, and the discovery of richer and more easily worked base-metal deposits in many other lands, caused Britain's small copper, lead, and tin mines to lapse into comparative insignificance. Apart from coal, iron ore (mostly low-grade), barytes, china-clay, fluorspar, gypsum, salt, and strontium, the United Kingdom is now almost wholly dependent on Empire and foreign sources for her mineral supplies, the severance of which would cripple much of her industrial life.

Even the far-flung *British Empire* must rely almost entirely upon outside sources for antimony, borates, mercury, molybdenum, potash, and sulphur, and has to import from outside the Empire considerable tonnages of other minerals, including bauxite, magnesite, and phosphates. On the other hand she has a virtual world control of nickel, gold, platinum, asbestos, and strontium, together with an excess of lead, zinc, tin, chromite, manganese, diamonds, sheet mica, radium, and uranium. In 1900, the *United States of America* displaced Great Britain as the world's foremost producer of coal and iron, and her present position as the premier manufacturing country is due to her immense mineral wealth, which includes abundant reserves of fuels, iron, copper, lead, zinc, phosphates, sulphur, &c. (see table on p. 212). Nevertheless in pre-war years the U.S.A. had to import 95 per cent of the manganese essential for her enormous steel output, and in addition to being devoid of domestic resources of tin, nickel, and diamonds, she lacks adequate supplies of chromium, tungsten, antimony, platinum, asbestos, sheet mica, flake graphite, and several other mineral commodities. We have previously referred to the tremendous increase in the development of mineral resources in the *Soviet Union* during the past two decades, and it may well be that as a result of intensive scientific prospecting the U.S.S.R. will become practically self-supporting, though at the present time she appears to lack sufficient resources of tin, tungsten, and possibly nickel.

The degree of *mineral self-sufficiency* of a country depends upon its capacity to supply requirements from its own domestic resources. For general purposes it is usual to base the consumption of a particular mineral on statistics of total home production plus imports, less exports. The table on p. 212 indicates the degree of self-sufficiency in the principal economic minerals for the major allied nations, according to 1938 statistics. Of the 23 minerals listed (excluding coal and oil), the British Empire was more or less deficient in 7, the Soviet Union in 10, the United States in 14, the French Empire in 15, China in 18, and Great Britain in 22. At that time Germany, Italy, and Japan were each less self-sufficient in mineral resources than the French Empire.

It should be stressed that this table merely reflects the extent of mineral production during 1938 in the countries named in relation to the amount consumed, and it may bear little connexion to the still undeveloped resources of those countries. Clearly, countries with large manufacturing capacity, such as the United States, may be deficient in certain minerals whilst actually producing much more of them than other less industrialized nations.

NATIONAL SELF-SUFFICIENCY IN PRINCIPAL MINERALS, 1938

Metallics							*Non-Metallics*						
	Great Britain	British Empire	United States	Soviet Union	French Empire	China		Great Britain	British Empire	United States	Soviet Union	French Empire	China
Antimony	o	o	—	o	o	+	Asbestos	o	+	o	+	o	o
Bauxite	o	=	—	—	+	o	Borates	o	o	+	—	o	o
Chromite	o	+	—	=	=	o	Diamonds	o	+	o	o	o	o
Copper	o	+	+	—	o	o	Fluorspar	+	+	=	=	=	o
Iron	—	=	=	+	+	=	Graphite	o	+	—	=	+	o
Lead	o	+	=	—	o	—	Magnesite	o	—	=	+	o	o
Manganese	o	+	o	+	o	—	Sheet Mica	o	+	o	=	o	o
Mercury	o	o	—	—	o	=	Phosphates	o	—	+	+	+	o
Nickel	o	+	o	—	=	o	Potash	o	o	—	=	+	o
Platinum	o	+	o	+	o	o	Sulphur	o	o	+	=	—	o
Tin	—	+	o	o	o	+							
Tungsten	o	=	—	o	o	+	Coal	+	+	+	+	=	+
Zinc	o	+	=	=	o	—	Oil	o	—	+	+	o	o

+ Surplus supply; minerals available for export.
= Supply adequate, or nearly so.
— Important deficiency.
o Negligible or absent.

Although there does not appear to be an immediate danger of a shortage in the world supply of any particular mineral, the fact that mineral deposits are exhaustible assets that are being depleted at an increasing rate focuses attention on the problem of available resources and their conservation. The accurate estimation of most mineral resources is usually impossible, for so many unpredictable factors are involved in connexion with the occurrence and discovery of mineral deposits and their workability. Under favourable circumstances it may be possible to appraise the reserves available within a certain mining field under existing economic conditions and technological practice, but in general only broad quantitative estimates can be made. When a mining company publishes the tonnage of ore reserves in a particular mine, it usually refers to the amount of ore proved or partly proved by survey, drilling, and underground development, without taking into consideration the additional possible ore that may be present but has still to be proved or partly proved. From the national viewpoint however, both the known and the unproved ore must be included in the total mineral resources. It must be emphasized too that improved methods of mining and metallurgical practice reduce costs and consequently may bring within economic range material that was previously discarded or considered unworkable. For example, efficient large-scale mining and the introduction of oil-flotation methods of ore-dressing made possible the successful exploitation of immense low-grade copper deposits in the United States and Chile, and of lead-zinc deposits in various parts of the world, which at the beginning of the century were regarded as worthless. It is reasonable to infer that just as the useless material of yesterday has to-day become valuable, so in the future mineral deposits now thought to be too poor to work or too inaccessible for profitable extraction will be mined successfully. Moreover, since the term mineral deposit, in the strict sense, refers to an accumulation of metallic or non-metallic minerals that can be profitably extracted, it follows that its size is not fixed but varies in conformity with price fluctuations.

In many parts of the world estimates have been published concerning the likely reserves of certain ore deposits, such as the copper resources of particular mines in Northern Rhodesia, North America, and Chile, the pyrite deposits of Spain, the manganese ores of the Soviet Union, the nickel ores of Ontario, and the phosphate deposits of the United States. On the other hand, little precise information is available relating to the tin and tungsten resources of the Far East and Bolivia, the antimony reserves of China, the mica deposits of India, and innumerable other deposits. In several countries, including the United States and parts of Europe, the potential mineral areas have already been intensively prospected by ordinary geological methods, and the rate of discovery of new deposits has declined rapidly during the present century. Elsewhere, there are still vast tracts that have never been adequately explored and where the prospects of finding important new mineral deposits by geological and geophysical surveys are reasonably good. With such considerations in mind we may attempt a qualitative estimate of the world resources of certain minerals, conscious that our assessments are likely to prove too conservative.

Iron and Ferro-Alloy Metals. The known reserves of *iron ore* in the United States, the Soviet Union, Brazil, Sweden, Lorraine-Luxembourg, and elsewhere are so colossal that there is no danger of a world shortage of iron for more than 100 years, even though the annual production of ore is maintained at the present level of 200 million tons.

Among the ferro-alloy metals the proved reserves of *manganese* ores are quite adequate to meet all likely demands for more than a century to come, the chief known sources of supply being the famous deposits of Nikopol and Chiaturi in the U.S.S.R., the ores of Postmasburg in South Africa, of the Central Provinces of India, Brazil, and the Gold Coast. The available evidence suggests that the Sudbury deposits of Ontario are capable of providing the bulk of the world's future *nickel* requirements for more than twenty-five years. Supplementary supplies exist in French New Caledonia, the U.S.S.R., and Finland, in addition to a large deposit recently opened up in the hinterland of Brazil. Although information concerning the extent of the *chromite* deposits of Turkey, the Transvaal, Southern Rhodesia, and the Soviet Union is rather vague, enough is known to ensure plentiful supplies of the mineral for several more generations. The position with regard to *tungsten* reserves is more problematical, though there is no reason to fear a serious dearth of the metal for many years, in view of the large resources of China and the supplementary deposits of Burma, Portugal, U.S.A., and Bolivia. The greatest *molybdenum* deposit in the world, at Climax, Colorado, contains sufficient ore to meet all normal requirements for more than twenty years, and large quantities of the metal can be recovered as a by-product of copper ores in North America and Eurasia. There appears to be no likelihood of a shortage of *vanadium* for a long time, for large ore reserves are known to occur at Minasragra in Peru, in Colorado, Northern Rhodesia, and S.W. Africa, in addition to extensive deposits recently discovered in Idaho; moreover, increasing quantities of the metal are now being recovered from oil refineries and from the soot collected from ships burning Mexican and South American fuel oil. The proved reserves of *cobalt*, mostly recoverable as a by-product of copper ores in Northern Rhodesia and the Belgian Congo, are enough to satisfy all normal demands for scores of years.

At the present rate of production more than a hundred years' supply of iron, manganese, and chromium are assured, and no serious deficiency in the other chief ferro-alloy metals is envisaged during the lifetime of the present generation, even if no more orebodies are discovered.

Base Metals. Despite the heavy production of *copper* during the recent war years, the known reserves of unmined metal are still probably sufficient to cover world requirements for about forty years at an average annual output of two million tons of metallic copper. It should be emphasized that the depletion of copper resources is offset to a considerable extent by the recovery and return to industry of important quantities of scrap (secondary) copper. Indeed, prior to 1939 it was not unusual for the United States to supply about two-thirds of her copper requirements from accumulated scrap metal. The extensive deposits of Chuquicamata in Chile, of Northern Rhodesia, the Belgian Congo, and the western U.S.A. are likely to continue as the main sources of new copper for many decades. There may be a shortage of primary *lead* in the United States, now the foremost producer, within this or the next generation. Although the proved reserves of lead ore throughout the world may guarantee little more than twenty years supply of the metal, the situation is fortunately relieved, as in the case of copper, by the high proportion of scrap metal returned to market. The known reserves of *zinc* have recently been estimated at more than fifty million tons of metal, equivalent to about thirty years supply at normal rates of consumption. Australia and Canada are likely to vie with the United States as principal producers of both lead and zinc.

Whilst plentiful supplies of *tinstone* still remain in the alluvial deposits of Malaya, Netherlands East Indies, and the Belgian Congo, little is known concerning the tonnage of ore available. As these gravel deposits become exhausted increasing attention will have to be paid to the mining of tin from veins and lodes. According to recent estimates the world reserves of *bauxite,* the chief source of aluminium, amount to 1,300 million tons, the principal deposits being in Hungary, the Gold Coast, British and Dutch Guiana, France, and Yugoslavia. These reserves are capable of providing two million tons of aluminium metal annually for about 150 years. Other possible sources of aluminium are nepheline, leucite, felspar, and andalusite (all silicates), alunite (a sulphate), and various clays, including china-clay. Since *magnesium* can be extracted commercially from sea-water and natural brines, and immense reserves of other raw materials, such as magnesite and dolomite, are also available, the resources of the important light metal, magnesium, are virtually without limit. The *mercury* reserves of the Almaden mine in Spain, and of Italy, are alone sufficient to satisfy world requirements for more than a hundred years at average rates of consumption, and China is thought to be capable of producing enough *antimony* to meet all needs for at least another fifty years.

Miscellaneous Minerals. Proved reserves of *sulphur*, a vital commodity in the chemical industry, are fully adequate to meet total requirements for more than half a century at the maximum pre-war rate of usage; vast deposits of pyrite (FeS_2) occur in southern Spain, and great quantities of native sulphur cap the salt-domes of Texas and Louisiana, besides existing in Sicily and the Caspian Sea region. No dearth of *platinum* metals is envisaged, for the nickel deposits of Ontario and the alluvial gravels of the Urals can supply enough of these metals for the present generation, and the low-grade ores of the Transvaal are capable of providing for more distant requirements. For scores of years to come the demand for *titanium* will probably be met mainly from the ilmenite-bearing beach sands of southern India, the massive titaniferous iron ores of Norway, the Urals and Adirondacks, and the rutile pegmatites of Virginia.

The most important agricultural fertilizers, *phosphates*, *potash*, and *nitrates*, occur in great abundance, sufficient to furnish world requirements for hundreds of years. Vast deposits of rock phosphate exist in the United States, North Africa, and the Pacific islands, and of the calcium phosphate mineral, apatite, in Northern Russia; of potash salts in the famous Stassfurt deposits of Germany, the western Urals, Alsace, Poland, Spain, and the United States, together with inexhaustible supplies contained in the oceans, natural brines, and the Dead Sea; of natural mineral nitrates in Chile, and of synthetic nitrates from coal and from the atmosphere.

From the gravels of S. W. Africa, the Belgian Congo, Angola, Sierra Leone, and the Gold Coast, this generation may confidently expect to gather its requirements of *industrial diamonds*, and although the proved reserves of the precious metals, *gold* and *silver*, may only be adequate for another thirty years or so, there is little doubt that valuable new discoveries will augment the available reserves. Of *asbestos*, *barytes*, *borates*, *diatomite*, *fluorspar*, *gypsum*, *rock salt*, and several other mineral raw materials there are more than enough reserves in widely scattered areas throughout the world to outlast the present century.

The proved reserves of certain minerals may approach exhaustion during the course of the present generation, but with improved methods of prospecting, mining, mineral concentration and refining, and scrap metal recovery, and with the more efficient use of mineral products and the employment of substitute materials, the bogey of mineral shortage will continue to recede. Despite the growing tendency in many countries towards nationalization of mineral rights, there is an urgent need to regard mineral resources as a world problem rather than a purely national one. To make the most effective use of our mineral heritage a full assessment of world resources should be undertaken so that an equitable policy of exploitation and distribution can be formulated and practised for the benefit of all mankind.

GLOSSARY OF MINERALS AND ROCKS

mentioned in the text

ALBITE, $NaAlSi_3O_8$, a soda plagioclase felspar, common in acid igneous rocks and certain metamorphic rocks.

ALUMS, hydrous sulphates of aluminium with an alkali metal.

ALMANDINE, $Fe_3Al_2(SiO_4)_3$, a deep red garnet, used as a gem-stone.

ALUNITE, $KAl_3(SO_4)_2(OH)_6$, a source of potash alum and a potential source of aluminium metal.

AMAZONSTONE, $KAlSi_3O_8$, a green variety of microcline felspar.

AMBER, a yellow fossil resin, used as a gem-stone.

AMETHYST, SiO_2, a purple transparent variety of quartz, used as a gem-stone.

AMPHIBOLES, an important group of rock-forming silicate minerals, including hornblende, common in igneous and metamorphic rocks.

ANDALUSITE, Al_2SiO_5, a mineral found in metamorphosed clayey rocks; valuable as an aluminous refractory material and as a minor source of aluminium metal.

ANDESITE, a volcanic rock occurring mainly as lava flows, and composed essentially of a medium plagioclase felspar together with one or more of the ferromagnesian minerals, such as biotite, hornblende, and a pyroxene.

ANHYDRITE, $CaSO_4$, occurs as a saline residue with gypsum and rock salt in sedimentary beds; used in the manufacture of sulphate of ammonia, sulphuric acid, nitro-chalk, and plasters.

ANORTHITE, $CaAl_2Si_2O_8$, a lime plagioclase felspar, common in ultrabasic igneous rocks.

APATITE, $Ca_5(PO_4)_3(F,Cl)$, a mineral valuable as a source of superphosphate fertilizers; mined on a large scale in the U.S.S.R.

APLITE, a fine-grained igneous rock composed chiefly of quartz and felspar, occurring as dykes and sills in and near granites.

ARAGONITE, $CaCO_3$, an orthorhombic mineral often found as acicular or columnar crystals.

ARGENTITE, Ag_2S, 'silver glance', one of the chief sources of silver, often found as microscopic inclusions in argentiferous galena.

ASBESTOS, a term which includes fibrous forms of amphibole and serpentine capable of resisting heat and being spun into yarn.

AUGITE, $Ca(Mg,Fe,Al)(Si,Al)_2O_6$, the principal member of the pyroxene group of rock-forming silicate minerals.

AUTUNITE, a lemon-yellow hydrated phosphate of calcium and uranium, which usually fluoresces in ultra-violet light.

AXINITE, $Ca_2(Fe,Mu)HAl_2B(SiO_4)_4$, occurs as clove-brown wedge-like crystals, and sometimes used as a gem-stone.

AZURITE, $2CuCO_3 . Cu(OH)_2$, an azure-blue oxidized copper ore-mineral, found in the upper parts of many copper lodes.

BADDELEYITE, ZrO_2, a principal source of zirconium, obtained from gravels in Brazil.

BALL CLAY, a sedimentary, plastic, refractory clay which fires white or nearly so, and is used chiefly as an ingredient of whiteware because of its high bonding quality.

BARYTES (= Barite), $BaSO_4$, 'heavy spar', the chief source of barium compounds; used in the manufacture of white paints, as a filler in paper, rubber, &c. and as a heavy drilling mud in the oil industry.

BASALT, the commonest of all lavas, is a black fine-grained rock consisting essentially of lime plagioclase felspar and augite, though olivine is also frequently present. Gas cavities formed near the tops of the basalt flows give rise to a vesicular or amygdaloidal structure.

BAUXITE, a rock composed of a mixture of hydrous aluminium oxides, such as *gibbsite*, $Al(OH)_3$, which is the principal raw material for the production of aluminium metal.

BENTONITE, a clay derived mainly from the alteration of volcanic dust, is commonly characterized by its property of absorbing large quantities of water and 'swelling' enormously in the process.

BERYL, $Be_3Al_2Si_6O_{18}$, practically the only source of beryllium; its varieties include the transparent precious stones, emerald and aquamarine.

BIOTITE, $K(Mg,Fe)_3(Al,Si)_4O_{10}(OH,F)_2$, one of the most abundant members of the mica group; usually dark brown.

BOG-IRON ORE is an impure deposit of limonite formed in bogs or swamps, largely by the action of algae and bacteria.

BORAX, $Na_2B_4O_7 . 10H_2O$, one of the two principal minerals used in the borate industry.

BORNITE, Cu_5FeS_4, purplish sulphide ore mineral of copper which becomes iridescent on exposure.

BORT, C, a dark, badly coloured or flawed diamond used in industry for abrasive and cutting purposes.

BRUCITE, $Mg(OH)_2$, a minor source of metallic magnesium.

CALCITE, $CaCO_3$, the commonest carbonate mineral, and the chief constituent of limestone, chalk, and marbles.

CARBONADO, C, a hard, black industrial diamond used for dies in wire drawing, for drill bits and diamond-tipped tools; obtained chiefly from Brazil.

CARBONATES, salts of carbonic acid, including such common minerals as calcite and dolomite.

CARNALLITE, $KMgCl_3.6H_2O$, a soluble chloride found associated with halite, sylvite, &c., in the salt deposits of Stassfurt in Germany; used as a source of magnesium and of potassium compounds.

CARNELIAN, SiO_2, a translucent yellowish-red variety of chalcedony, used as a semi-precious stone.

CARNOTITE, $K_2(UO_2)_2(VO_4)_2.8H_2O$, a soft yellow powdery mineral found in certain sandstones in Colorado, is a source of vanadium, radium, and uranium.

CASSITERITE, SnO_2, 'tinstone', the principal ore-mineral of tin, characterized by high specific gravity and brilliant lustre.

CELESTITE, $SrSO_4$, the chief source of strontium salts, is obtained mainly from the Yate district near Bristol.

CERUSSITE, $PbCO_3$, found in the oxidation zone of lead veins and ranks next to galena as an ore-mineral of lead.

CHALCEDONY, SiO_2, a minutely crystalline fibrous form of silica, often translucent and waxy in appearance; its varieties include agate, carnelian, flint, chert, and jasper.

CHALCOCITE, Cu_2S, 'copper glance', one of the most important copper ore-minerals, usually found in the zone of secondary sulphide enrichment of copper deposits.

CHALCOPYRITE, $CuFeS_2$, brass-yellow 'copper pyrites', the most abundant copper mineral, and one of the principal commercial sources of that metal.

CHALCOTRICHITE, Cu_2O, a red, fibrous form of cuprite, known as 'plush copper'.

CHALK, a soft white limestone composed of finely divided calcium carbonate (calcite) and containing myriads of minute fossil foraminifera.

CHAMOSITE, a complex greenish hydrous iron silicate, commonly occurring as rounded grains in oolitic iron ores, such as those stretching southwards from Yorkshire into Northamptonshire.

CHILE SALTPETRE, $NaNO_3$, soda nitre or nitratine, the chief natural source of nitrates, mainly used as fertilizers; the only commercial deposits are in the deserts of northern Chile.

CHINA-CLAY, a soft white rock largely composed of the mineral *kaolinite*, and derived from the decomposition of felspar by the action of water and carbon dioxide.

CHLORITE, approximately $(Mg,Fe)_5(Al,Fe)_2Si_3O_{10}(OH)_8$, an abundant green scaly mineral, usually formed as an alteration product of biotite, hornblende, or other ferromagnesian silicates.

CHROMITE, $FeCr_2O_4$, the only ore-mineral of chromium, occurs in association with basic igneous rocks.

CINNABAR, HgS, a red heavy mineral, the only important source of mercury.

CLAY, a fine-textured earthy rock which is usually plastic when wet, and hardens under fire; it consists chiefly of hydrous aluminium silicates, together with minute flakes of mica and chlorite, particles of quartz, and some colloidal material.

COAL, a black carbonaceous deposit formed by the burial and compaction of ancient vegetable remains.

COBALTITE, $CoAsS$, a silver-white ore-mineral of cobalt.

COLUMBITE, $(Fe,Mn)Nb_2O_6$, grades into tantalite as niobium (columbium) is replaced by tantalum; columbite, the chief source of niobium, is obtained principally from Nigeria.

CONGLOMERATE, a cemented deposit of pebbles or gravels.

CORDIERITE, $(Mg,Fe)_2Al_4Si_5O_{18}$, occurs chiefly as a mineral in metamorphic rocks; sometimes used as a blue gem-stone, 'water sapphire.'

CORUNDUM, Al_2O_3, second only to diamond in hardness, is a valuable abrasive mineral; gem varieties include deep red *ruby* and blue *sapphire*; the blackish variety, mixed with iron oxide minerals, is known as *emery*.

COVELLITE, CuS, an indigo-blue minor ore of copper, found in the zone of secondary sulphide enrichment of copper deposits.

CUPRITE, Cu_2O, 'ruby copper', a red oxide of copper occurring in the upper oxidized parts of copper deposits, constitutes an ore-mineral of copper.

DESCLOIZITE, $PbZn(OH)(VO_4)$, a source of vanadium, occurs in the oxide zone of certain lead-zinc deposits, notably at Broken Hill in Northern Rhodesia, and Tsumeb in S. W. Africa.

DIAMOND, C, the hardest of minerals and most important of the gem-stones; widely used in industry as a cutting and abrasive agent.

DIASPORE, $AlO(OH)$, an abundant constituent of many bauxites, and a decomposition product of corundum.

DIATOMITE (= diatomaceous earth, kieselguhr, or tripoli-powder), is a friable, porous, and light rock formed by the accumulation of myriads of algae called diatoms, and consists largely of opaline silica.

DIOPSIDE, $CaMgSi_2O_6$, a pale green member of the pyroxene group.

DIORITE, a coarse-grained intrusive igneous rock composed of a medium plagioclase felspar and hornblende, with or without biotite.

DOLERITE, an igneous rock consisting essentially of a lime-rich plagioclase felspar and augite, with olivine as a frequent constituent; occurs in dykes and sills.

DOLOMITE, $CaMg(CO_3)_2$, a rhombohedral carbonate mineral, often with curved crystal faces; occurs in extensive beds of dolomite rock, and is a valuable building stone, refractory material, source of magnesium metal, and ingredient of special cements.

EMERALD, $Be_3Al_2Si_6O_{18}$, the green transparent gem variety of beryl.

ENSTATITE, $MgSiO_3$, an orthorhombic member of the pyroxene group, common in many basic igneous rocks.

FELSPARS, silicates of aluminium with potassium, sodium, calcium, and, rarely, barium; they are the most important group of rock-forming minerals, especially in igneous rocks; the many varieties include orthoclase and plagioclase felspars.

FLINT, a minutely crystalline form of chalcedonic silica (SiO_2), chiefly found as irregular nodules in the Chalk.

FLUORSPAR (= Fluorite), CaF_2, a mineral valuable as a flux in steel-making, in the manufacture of opalescent glass and enamels, and the preparation of hydrofluoric acid; a purple variety, 'Blue John', is used as an ornamental stone for vases, &c.

FORSTERITE, Mg_2SiO_4, the magnesian member of the olivine group, usually found in metamorphosed limestones.

FULLER'S EARTH, a highly absorptive clay of low plasticity, widely used to filter and clarify oils and greases, and to clean cloth.

GABBRO, a granular basic intrusive igneous rock consisting chiefly of lime plagioclase felspar and augite.

GALENA, PbS, the most important ore-mineral of lead, usually contains silver, and is a main source of that metal; it occurs chiefly in veins and replacement deposits in limestone.

GARNETS, silicates of various divalent and trivalent metals, e.g. the variety *pyrope* is $Mg_3Al_2(SiO_4)_3$; often used as an abrasive, and some varieties serve as gem-stones.

GARNIERITE, $(Ni,Mg)SiO_3.nH_2O$, a green earthy ore of nickel found in certain serpentines, notably those of New Caledonia.

GIBBSITE, $Al(OH)_3$, one of the chief constituents of the rock bauxite, the principal ore of aluminium.

GNEISS, a coarsely foliated or banded metamorphic rock composed essentially of felspar, quartz, and a dark mineral, such as biotite mica or hornblende.

GOSSAN, a Cornish term, equivalent to the German 'iron hat', applied to the oxidized or weathered outcrop of a sulphide-bearing lode, and consisting principally of hydrated iron oxides (limonite).

GRANITE, a light-coloured granular intrusive igneous rock consisting chiefly of potash and soda felspars, quartz, and a small amount of mica, hornblende, or a pyroxene.

GRANODIORITE, an intrusive igneous rock, somewhat similar in appearance to granite, but containing more plagioclase felspar and less quartz.

GRAPHITE, C, 'Plumbago', 'Black Lead', a soft, black, scaly form of carbon, used in the manufacture of refractory crucibles, pencils, paints, lubricants, and for facings on foundry moulds.

GREENOCKITE, CdS, occurs as a yellow earthy coating on zinc minerals, particularly sphalerite, and is an important source of cadmium.

GUANO, a phosphatic deposit formed from the droppings of fish-eating sea birds on arid coasts and oceanic islands.

GYPSUM, $CaSO_4 . 2H_2O$, occurs in sedimentary rocks usually as a saline residue formed by the evaporation of sea-water; used for making plaster of Paris, as a retarder in Portland cement, and as a filler in paints, paper, &c.

HALIDES are compounds of the metals with the halogen elements, including chlorine and fluorine; for example, *halite*, NaCl.

HALITE (= Rock salt, common salt), NaCl, occurs as extensive beds formed by the evaporation of sea-water; used for culinary and preservative purposes, but mainly in the manufacture of soda ash (sodium carbonate) and salt cake (sodium sulphate) for use in glass-making, soap-making, &c., and in the preparation of metallic sodium.

HEMATITE, Fe_2O_3, the most important ore of iron; its varieties include the black lustrous 'specular iron', and the reddish rounded forms of 'kidney ore'.

HEMIMORPHITE, $Zn_4Si_2O_7(OH)_2 . H_2O$, formerly 'Calamine' in America, a minor ore of zinc, found in the oxidized parts of zinc deposits.

HORNBLENDE, approximately $Ca_2Na(Mg,Fe)_4(Al,Fe)_3Si_6O_{22}(O,OH)_2$, a widely distributed dark-green member of the amphibole group.

HORNFELS, a fine granular rock with 'horny' fracture, formed chiefly by the metamorphism of sediments near an igneous intrusion, and composed essentially of quartz, felspars, and micas, with or without such minerals as andalusite, cordierite, garnet, and diopside.

ICE, H_2O, the solid form of water, existing at or below 0° C.

ICELAND SPAR, $CaCO_3$, a pure transparent form of calcite, used in optical instruments to produce polarised light.

ILMENITE, $FeTiO_3$, 'titanic iron ore', the principal source of titanium, used chiefly in the manufacture of white paints, and obtained mainly from beach sands in S. W. India.

IRON PYRITES (= Pyrite), FeS_2, the commonest sulphide mineral, chiefly used for making sulphuric acid, but also as a source of sulphur dioxide needed in the preparation of wood pulp for the paper industry, and as a source of sulphur (brimstone).

JADE, a white to dark-green semi-precious stone, includes two minerals—the amphibole nephrite (true jade), and the pyroxene jadeite, obtained chiefly from upper Burma.

JADEITE, $NaAlSi_2O_6$, the principal jade mineral.

KAOLINITE, $Al_2Si_2O_5(OH)_4$, a common alteration product of felspar, and the main constituent of china-clay.

KERNITE (= Rasorite), $Na_2B_4O_7 . 4H_2O$, the principal source of borax, obtained from the Mohave Desert in California.

KIMBERLITE, a fragmented serpentinized olivine rock, often rich in enstatite and phlogopite mica, occurring in the diamond-pipes of South Africa.

KYANITE, Al_2SiO_5, a bladed blue mineral, valuable as an aluminous refractory material, especially for use in sparking plugs and highly refractory porcelains.

LABRADORITE, a lime plagioclase felspar, widespread in basic igneous rocks, and often displays an iridescent play of colours.

LAPIS LAZULI, a metamorphosed limestone of deep azure-blue colour (due to the presence of the mineral *lazurite*, approximately $Na_4Al_3Si_3O_{12}S$), used as an ornamental stone, and formerly as the paint pigment 'ultramarine'.

LEPIDOLITE, $K(Li,Al)_3(Al,Si)_4O_{10}(OH,F)_2$, a lithia mica valuable in glass-making, ceramics, and as a source of lithium compounds; occurs in granite-pegmatite veins.

LEUCITE, $KAlSi_2O_6$, found in potash-rich lavas, and sometimes used in the production of potash-fertilizer and potash-alum; it is a potential source of aluminium metal.

LIGNITE (= Brown coal), a coal of the lowest rank, resembling woody peat, but containing a higher proportion of carbon and more than 20 per cent of water.

LIMESTONE, a sedimentary rock consisting essentially of calcium carbonate (calcite), often with small amounts of magnesium carbonates and impurities, such as quartz grains.

LIMONITE (= Brown hematite, bog-iron ore), approximately $FeO(OH) . nH_2O$, a common alteration product of other iron-bearing minerals, and an important iron ore and yellow ochre pigment.

LINNAEITE, Co_3S_4, a principal source of cobalt, obtained chiefly as a by-product from the copper deposits of Northern Rhodesia and the Belgian Congo.

LODESTONE, Fe_3O_4, a variety of magnetite which acts as a natural magnet and exhibits magnetic polarity.

MAGNESITE, $MgCO_3$, a rhombohedral carbonate mineral used for making refractory bricks, magnesium salts, oxychloride cements, and in the manufacture of metallic magnesium.

MAGNETITE, Fe_3O_4, a strongly magnetic iron ore mineral, and an important source of iron, especially in northern Sweden.

MALACHITE, $Cu_2CO_3(OH)_2$, a bright green copper carbonate, found in the oxidized portions of copper deposits; a valuable ore of copper, and an ornamental material used for making vases, &c.

MARBLE, a metamorphosed limestone composed of interlocking grains of calcite, white when pure but often coloured by impurities, such as green serpentine.

MERCURY (= Quicksilver), Hg, a liquid mineral which solidifies at –39°C; native mercury is rare.

MICAS, a group of silicate minerals characterized by perfect cleavage, flexibility, elasticity, infusibility, and high dielectric strength; some members are especially valuable as insulating materials in electrical apparatus.

MILLERITE, NiS, 'hair pyrites', an uncommon sulphide mineral usually found as brass-yellow hair-like tufts.

'MINETTE ORE', the oolitic limonite ore of the Lorraine-Luxembourg region, of great importance as a source of iron.

MOLYBDENITE, MoS_2, a soft, lead-grey mineral, the chief source of molybdenum, usually found in association with granitic rocks.

MONAZITE, $(Ce,La,Di)PO_4$, a yellowish-brown phosphate of the rare-earth metals, is the main source of thorium, mesothorium, and cerium; it is chiefly obtained from coastal sands of S. W. India.

MONZONITE, a course-grained intrusive igneous rock intermediate between syenite and diorite, containing more plagioclase than orthoclase felspar, and including small amounts of hornblende and biotite, but seldom any quartz.

MOONSTONE, a variety of potash felspar containing minute inclusions of soda felspar which give rise to an opalescent play of colours.

MOTHER-OF-PEARL, an iridescent lustrous material lining the interior of certain molluscs, the pearly lustre resulting from the interference of light reflected from minute overlapping plates or needles of aragonite (calcium carbonate).

MUSCOVITE, $KAl_2(Al,Si_3)O_{10}(OH)_2$, an abundant white mica, valuable mainly as an electrical insulator, and as a transparent non-inflammable material for windows in furnaces, stoves, &c.

NATIVE ELEMENTS are those found in an uncombined form as natural minerals, for example, gold, copper, arsenic, carbon, and sulphur.

NEPHELINE, approximately $NaAlSiO_4$, a source of aluminium valuable in making glass, and used in the U.S.S.R. as a raw material for the manufacture of metallic aluminium.

NITRATES, salts of nitric acid, HNO_3; for example, soda nitre, $NaNO_3$.

NORITE, a granular intrusive igneous rock akin to gabbro, composed essentially of lime plagioclase felspar and the pyroxene, hypersthene $(Mg,Fe)SiO_3$.

OBSIDIAN, a black volcanic glass of rhyolitic composition, which breaks with a conchoidal fracture.

OCHRE, a mixture of limonite, hematite, and clay used for yellow, brown, and red natural pigments, such as yellow and red ochres and siennas.

OLIGOCLASE, a soda-lime plagioclase felspar, common in acid to intermediate igneous rocks.

OLIVINE, $(Mg,Fe)_2SiO_4$, the principal member of the olivine group, typically found in ultrabasic igneous rocks; used as a refractory material, and as the transparent green gem-stone, peridot.

ONYX, SiO_2, a banded variety of chalcedonic silica, used as a semi-precious stone.

OOLITIC LIMESTONE, a variety of limestone made up of small spherical or ellipsoidal grains resembling fish roe, formed by the chemical precipitation of calcium carbonate in successive layers around a nucleus.

OPAL, $SiO_2.nH_2O$, a mineral gel, often prized as a gemstone; diatomaceous earth consists of myriads of opaline tests of diatoms, and is used as a filtering medium, abrasive, filler, and insulator.

ORTHOCLASE, $KAlSi_3O_8$, a common variety of felspar, chiefly used in the manufacture of porcelain and glazed ware, and as a source of alumina in glass-making.

OSMIRIDIUM (= Iridosmine), (Ir,Os), a natural alloy of osmium and iridium, used for fountain-pen nibs and in electroplating.

OXIDES, compounds of oxygen with a metal, e.g. hematite, Fe_2O_3; some oxide minerals contain water or the hydroxyl (OH), e.g. goethite, FeO(OH).

PATRONITE, a substance of indefinite composition formerly thought to be the sulphide, VS_4, is an important source of vanadium at Minas Ragra in Peru.

PEGMATITE, a very coarse-grained intrusive igneous rock commonly occurring as dykes and veins in and near granites; it consists of quartz, felspar, and mica, often together with minor amounts of beryl, topaz, tourmaline, uranium minerals, &c.

PENTLANDITE, $(Fe,Ni)_9S_8$, the principal ore mineral of nickel, occurs intimately associated with pyrrhotite in basic igneous rocks, as at Sudbury in Ontario.

PERIDOTITE, a granular intrusive igneous rock composed mainly of olivine, with or without augite, hornblende, biotite, and iron oxides, but with only a trivial amount of felspar.

PHLOGOPITE, $KMg_3(Al,Si_3)O_{10}(OH)_2$, a brown mica, used chiefly as a high-grade electrical insulator.

PHOSPHATE DEPOSITS, include marine sedimentary beds of phosphate rock, phosphatic marls and limestones, guano, residual concentrations derived from phosphatic beds, and apatite deposits.

PHYLLITE, a lustrous micaceous rock of metamorphic origin, intermediate between slate and mica-schist, due to the stress metamorphism of material which was originally a fine-grained muddy sediment.

PITCHBLENDE, the black pitch-like variety of uraninite, UO_2, the main source of uranium and of radium.

PLAGIOCLASE FELSPARS, the commonest of all rock-forming minerals, range in composition from $NaAlSi_3O_8$ (albite) to $CaAl_2Si_2O_8$ (anorthite), and are widely distributed in igneous and metamorphic rocks.

POLLUCITE, $CsAlSi_2O_3.nH_2O$, a rare mineral found in pegmatites, is the chief source of caesium.

PORPHYRITE, an igneous rock of intermediate composition consisting of large crystals of medium plagioclase felspar and hornblende, in a fine-grained groundmass of felspar with some hornblende and biotite; usually occurs as dykes and sills.

PSILOMELANE, probably $BaMn^{2}Mn^{4}_{8}O_{16}(OH)_4$, a black oxide of manganese, and a principal source of that metal.

PYRITE (= Iron pyrites), FeS_2, the most common sulphide mineral, chiefly used for making sulphuric acid.

PYROLUSITE, MnO_2, a common black oxide of manganese, important as an ore mineral of manganese.

PYROXENES, an important group of silicate minerals, including augite and diopside, common in many igneous and metamorphic rocks.

PYRRHOTITE, approximately FeS, 'magnetic pyrites', occurs chiefly in basic igneous rocks such as gabbro and norite, and often intimately mixed with the principal nickel mineral, pentlandite.

QUARTZ, SiO_2, a common mineral in acid igneous rocks and many metamorphic rocks, besides being the main constituent of sandstones; as sand it is used in the building trade, glass-making, foundry work, &c., and as an acid flux in smelting; as rock crystal used in electrical equipment and as a semi-precious stone; as sandstone and quartzite it forms a valuable building stone.

QUARTZITE, a metamorphic rock derived by the recrystallization of sandstone, and composed essentially of an interlocking mosaic of quartz grains; the term also connotes a sandstone cemented by silica.

QUARTZ PORPHYRY, an igneous rock containing large crystals of quartz and orthoclase felspar set in a fine-grained groundmass of quartz and felspar, with occasional flakes of mica; it occurs as dykes and sills in granitic areas.

RHYOLITE, a fine-grained acid lava, the volcanic equivalent of granite, composed essentially of quartz and alkali felspar, and often characterized by flow-structure or banding.

ROCK CRYSTAL, a colourless transparent variety of quartz, SiO_2, often found as well-formed crystals.

ROCK SALT (= Halite, common salt), $NaCl$.

ROSCOELITE, $KV_2AlSi_3O_{10}(OH)_2$, a greenish vanadium mica which constitutes an ore mineral of vanadium in Colorado and Utah.

RUBY, a deep-red transparent gem-variety of corundum, Al_2O_3, obtained mainly from Burma, Siam, and Ceylon.

RUTILE, TiO_2, an important source of titanium, used for making white paints, for coating electric welding rods, in electrodes, and to a limited extent in steel-making.

SANDSTONE, a sedimentary rock composed predominantly of quartz grains, and representing a compacted bed of sand.

SAPPHIRE, a transparent blue gem-variety of corundum, Al_2O_3.

SCHEELITE, $CaWO_4$, a subordinate ore mineral of tungsten, found in pegmatites and veins associated with granitic rocks.

SCHIST, a metamorphic rock composed largely of flaky minerals such as mica, chlorite and talc, or of prismatic minerals like hornblende, which is characterized by a parallel lamination called 'schistosity'.

SERPENTINE, a rock consisting almost wholly of the mineral serpentine, $Mg_3Si_2O_5(OH)_4$, and derived by the metamorphism of an olivine-rich rock.

SHALE, a laminated sedimentary rock formed by the consolidation of mud, clay, or silt, and composed chiefly of the so-called 'clay minerals', such as kaolinite.

SIDERITE (= Chalybite), $FeCO_3$, a rhombohedral carbonate mineral, valuable as an ore of iron, notably in Britain.

SILICATES, the predominant chemical class among minerals, containing various metallic elements in combination with silicon and oxygen.

SILLIMANITE (= Fibrolite), Al_2SiO_5, a mineral found in metamorphosed clayey rocks, used in making refractory and electrical porcelains.

SILVER, Ag, a native element, found principally in the oxidized zone of ore deposits, is a minor source of silver.

SLATE, a fine-grained metamorphic product of shales, mudstones, or volcanic dusts which have suffered intense compression; it can be split into thin slabs along the 'slaty cleavage', the direction of which is independent of the original bedding planes.

SMALTITE, $CoAs_2$, a silver-grey ore-mineral of cobalt, notably at Cobalt in Ontario.

SMITHSONITE, $ZnCO_3$, formerly 'Calamine' in Britain, a zinc ore-mineral, usually occurring in limestone as an alteration product of sphalerite, ZnS.

SOAPSTONE, usually an impure massive form of talc, $Mg_3Si_4O_{10}(OH)_2$, capable of being quarried in large pieces.

SPECULAR HEMATITE, Fe_2O_3, a black variety of hematite possessing a splendid metallic lustre.

SPHALERITE (= Zinc blende), ZnS, the principal ore-mineral of zinc, a metal chiefly used for galvanizing iron, for die-castings, electric batteries, paints, and alloys such as brass.

SPINEL, $MgAl_2O_4$, includes the clear red variety known as ruby spinel, and the rose-red form, balas ruby.

SPODUMENE, $LiAlSi_2O_6$, a member of the pyroxene group, valuable as a source of lithium; the lilac 'kunzite', and the emerald-green 'hiddenite' are gem varieties of spodumene.

STAUROLITE, $Fe(OH)_2Al_4Si_2O_{10}$, a brown mineral commonly of metamorphic origin, and often found as cross-shaped twins.

STIBNITE (= Antimonite), Sb_2S_3, the chief ore-mineral of antimony, principally used in hardening lead.

SULPHATES, include minerals whose formula contains the sulphate radical, SO_4; for example, anhydrite, $CaSO_4$.

SULPHIDES are those minerals which consist mainly of combinations of sulphur with various metals; they include the majority of metallic ore-minerals, such as galena, PbS, and sphalerite, ZnS.

SULPHUR, S, a native element, often found near volcanic craters, and in sedimentary rocks associated with gypsum and limestone, is chiefly used in the manufacture of sulphuric acid, insecticides, and wood pulp for paper-making.

SYENITE, a granular intrusive igneous rock composed essentially of alkali felspar (usually orthoclase), with hornblende as the characteristic ferromagnesian mineral.

TALC, $Mg_3Si_4O_{10}(OH)_2$, a soft flaky mineral typically found in metamorphic rocks, is used in making paints, ceramics, electrical insulators, paper, toilet preparations, and as a filler in the rubber, plastics, and other industries; in the massive forms known as 'steatite' and 'soapstone' it is employed as slabs for electrical switchboards, table-tops, tailor's chalk, &c.

TANTALITE, $(Fe,Mn)Ta_2O_6$, with some Nb (= Cb), occurs in association with granitic rocks, and is the chief source of tantalum.

THORIUM, Th, a radioactive element principally obtained from the phosphate mineral, monazite.

TINSTONE (= Cassiterite), SnO_2, practically the only ore-mineral of tin, is found in association with granitic rocks.

TOPAZ, $Al_2SiO_4\ (F,OH)_2$, usually found in granitic rocks, including tin-bearing pegmatites, is used as a gem-stone.

TOURMALINE, a complex silicate of boron and aluminium, with a variable content of Na, Fe, Li, and Mg, found in acid igneous rocks, and often used as a gem-stone.

TREMOLITE, $Ca_2Mg_5Si_8O_{22}(OH)_2$, a member of the amphibole group, typically found in metamorphosed dolomitic limestones, and sometimes used as an asbestos material.

TUFF, a volcanic rock formed by the compaction of fine dust and small fragments emitted from volcanoes.

TURQUOISE, $Al_2(OH)_3PO_4.H_2O + x\text{Cu}$, a bluish mineral found in veinlets cutting decomposed volcanic rocks, is used as a gem-stone.

URANINITE, UO_2, the principal source of radium and uranium, notably obtained from the Great Bear Lake region of Canada, and from the Belgian Congo; the velvet-black variety is called 'pitchblende'.

VANADINITE, $Pb_5Cl(VO_4)_3$, found in the oxidation zone of certain lead deposits, is a source of vanadium and a minor ore of lead.

VERMICULITE, $(Mg,Fe)_3(Si,Al,Fe)_4O_{10}(OH)_2.4H_2O$, a brown mica-like mineral which swells and exfoliates on heating, and is used for sound and heat insulation.

WATER, H_2O, exists as a solid, ice, at or below 0°C; as a liquid, water, between 0° and 100°C; and as a gas, steam, above 100°C, and as aqueous vapour in the atmosphere at all temperatures.

WAVELLITE, $Al_3(OH)_3(PO_4)_2.5H_2O$, a rare mineral usually found as small spherical aggregates with a radiating structure.

WILLEMITE, Zn_2SiO_4, a greenish ore-mineral of zinc, especially at Franklin Furnace, New Jersey, U.S.A.; notable for its bright fluorescence in ultra-violet light.

WOLFRAMITE (= Wolfram), $(Fe,Mn)WO_4$, the chief ore-mineral of tungsten, usually found in quartz veins and pegmatites associated with granites.

ZEOLITES, a family of hydrous silicates of aluminium with sodium and calcium as principal bases, characterized by ready fusibility, and typically found within cavities and cracks in basic lavas; *natrolite*, $Na_2Al_2Si_3O_{10}.2H_2O$, is a common member of the family.

ZINC BLENDE (= Sphalerite), ZnS, the most important ore-mineral of zinc, chiefly found in veins and replacement deposits in limestone.

ZIRCON, $ZrSiO_4$, a principal source of zirconium, is used as a refractory material and, when transparent, as a gem-stone.

THE GEOLOGICAL TABLE AND TIME SCALE

Eras	*Periods and Systems*		*Approximate age of Base of System in millions of years*
CAINOZOIC	Quaternary	Recent	
		Pleistocene	1
	Tertiary	Pliocene	
		Miocene	
		Oligocene	
		Eocene	70
MESOZOIC	Cretaceous		120
	Jurassic		150
	Triassic (New Red Sandstone)		190
PALAEOZOIC	Permian (New Red Sandstone)		220
	Carboniferous		280
	Devonian (Old Red Sandstone)		320
	Silurian		350
	Ordovician		400
	Cambrian		500
PRE-CAMBRIAN	The older rocks of this era are called Archaean at least		1,750
ORIGIN OF THE EARTH	at least		2,000

The PRINCIPAL METALLOGENETIC EPOCHS (i.e. periods of intense mineralization) took place during the following times:

(i) Pre-Cambrian, (ii) Middle Palaeozoic, (iii) Late Palaeozoic, (iv) Permo-Triassic (mainly sedimentary deposits, e.g. salt, gypsum, and potash), (v) Jurassic (mainly sedimentary deposits, e.g. oolitic iron ores of Europe), (vi) Late Mesozoic, (vii) Early Tertiary, and (viii) Late Tertiary.

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